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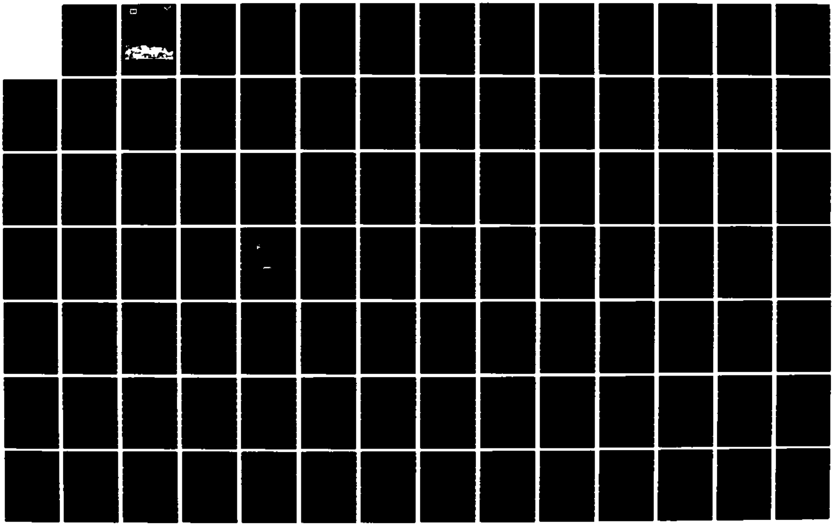

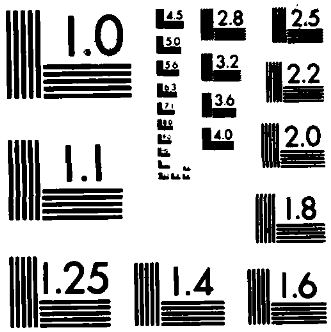
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TECHNICAL REPORT GL-83-1

CAVITY DETECTION AND DELINEATION RESEARCH

Report 2
SEISMIC METHODOLOGY: MEDFORD CAVE SITE, FLORIDA

by

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Report 2 of a Series

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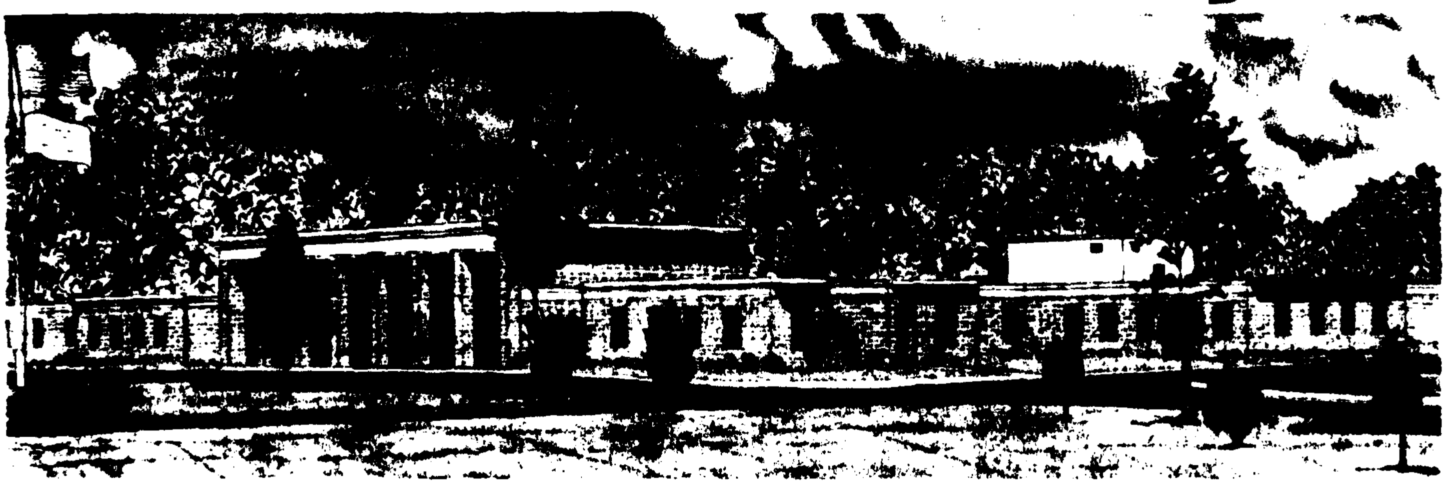

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CAVITY DETECTION AND DELINEATION RESEARCH

	Title	Author
Report 1:	Microgravimetric and Magnetic Surveys: Medford Cave Site, Florida	Dwain K. Butler
Report 2:	Seismic Methodology: Medford Cave Site, Florida	Joseph R. Curro, Jr.
Report 3:	Acoustic Resonance and Self-Potential Applications: Medford Cave and Manatee Springs Sites, Florida	Stafford S. Cooper
Report 4:	Microgravimetric Survey: Manatee Springs Site, Florida	Dwain K. Butler, Charlie B. Whitten, Fred L. Smith
Report 5:	Electromagnetic (Radar) Techniques Applied to Cavity Detection	Robert F. Ballard, Jr.

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As part of a research program designed to find a quick and economical methodology to detect and delineate cavities, seismic technology was applied to the cavity problem at the Medford Cave site, Florida. Six seismic techniques consisting of surface refraction, constant-spacing, fan-shooting, surface shear-wave, uphole refraction, and crosshole investigations were employed at the site in an effort to detect and delineate cavity features. The results of these tests indicated that the surface refraction, constant-spacing, and crosshole techniques detected and —— (Continued)

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partially delineated cavities. Their degree of success was as follows:

a. Surface refraction tests. Only one out of seven tests successfully detected a cavity (6 to 11 ft high and 31 ft wide with the roof about 11 ft below ground surface). Partial delineation was accomplished in that the start of the cavity was defined.

b. Constant-spacing tests. All three of the constant-spacing surveys detected cavities which ranged in size from 5 to 8 ft high and 4 to 13 ft wide with the roofs being 9 to 20 ft below the ground surface. Partial delineation was achieved in that the cavities were located in plan but not in depth to or height of the cavities.

c. Crosshole tests. The crosshole P-wave test conducted across a cavity indicated significantly lower velocities in the area of the cavity (14 ft high and 9 ft wide with the roof 19 ft below ground surface). It will be noted that the crosshole technique cannot detect a cavity, per se, but will identify weak zones or low-velocity layers that may or may not be void-related. Partial delineation using the depth to and thickness of the zone of lower velocities was accomplished within 2 ft of the cavity depth and height. Planar delineation (diameter and location of cavity between borings) was not achieved.

In summary, the constant-spacing technique is the only surface seismic test procedure recommended for use in cavity detection-delineation and the crosshole P-wave technique is the only subsurface method recommended.

PREFACE

This investigation was conducted by the U. S. Army Engineer Waterways Experiment Station (WES) for the Office, Chief of Engineers (OCE), U. S. Army, under the Materials - Rock Research Program, CWIS Work Unit 31150 entitled "Remote Delineation of Cavities and Discontinuities in Rock." Mr. P. R. Fisher, OCE, was the Technical Monitor, and Dr. D. C. Banks, WES, was the Rock Research Program Manager.

This field of study was conducted intermittently during the period May 1979 to November 1980. Individuals contributing to the planning, testing, and analysis phases of the investigation were Messrs. J. R. Curro, Jr., D. K. Butler, R. F. Ballard, Jr., R. E. Wahl, D. E. Yule, J. L. Llopis, D. H. Douglas, and M. M. Carlson of the Earthquake Engineering and Geophysics Division (EEGD), Geotechnical Laboratory (GL). The work was performed under the direct supervision of Dr. A. G. Franklin, Chief, EEGD, GL, and under the general supervision of Dr. W. F. Marcuson III, Chief, GL.

Special acknowledgement is given to Messrs. J. D. Gammage, William Stelz, and Bill Wisner, and Dr. Robert Ho of the Florida Department of Transportation, Gainesville, Fla., for their assistance in site selection activities and for providing some drilling support.

Commanders and Directors of WES during the conduct of the investigation and preparation of this report were COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Mr. Fred R. Brown was Technical Director.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	4046.873	square metres
feet	0.3048	metres
inches	25.4	millimetres
miles (U. S. statute)	1.609347	kilometres
pounds (force)	4.448222	newtons
pounds (mass)	0.4535924	kilograms

CAVITY DETECTION AND DELINEATION RESEARCH

SEISMIC METHODOLOGY: MEDFORD CAVE SITE, FLORIDA

PART I: INTRODUCTION

Background

1. In order to design and construct water resource structures in any of the many karstic regions in the nation, it is necessary to understand the nature, extent, and positions of the cavities in the limestone foundation rock. For existing structures built in karstic terrain, remedial measures to control excessive seepage are sometimes necessary. An extremely important part of either foundation preparation during construction or postconstruction remedial measures is the determination of the location and geometry of the cavities. Presently, this determination can only be done by direct penetration of cavities by foundation excavations and by borings, which are time- and cost-ineffective. A quick and economical methodology is needed to locate cavities. To partially address the above requirement, a research program entitled "Improvement of Geophysical Methods," funded by the Office, Chief of Engineers, U. S. Army, was initiated at the U. S. Army Engineer Waterways Experiment Station (WES) in 1974. Major accomplishments under this work unit were the construction of a controlled test facility incorporating artificial cavities at WES in 1976 and the holding of a Symposium on Detection of Subsurface Cavities at WES in 1977. Results of geophysical investigations conducted at the test facility have been reported by Butler and Murphy (1980) and the proceedings of the symposium were published in 1977 (Butler, 1977).

2. In 1977, the general approach of this research program was altered to be more responsive to the identified problems of field-operating agencies and directly address high-priority mission problem statements. In accordance, the work unit title was changed to "Remote

Delineation of Cavities and Discontinuities in Rock" to reflect this new direction.

Objective

3. The objective of this study was to use various seismic techniques at a natural test site (cavity in rock) and evaluate their effectiveness for cavity detection and delineation.

Scope

4. To meet the objective, two natural test sites were selected for feasibility and in-depth studies using seismic methodology. The sites, both located in Florida, were Medford Cave and Manatee Springs with the former being an air-filled system and the latter a water-filled system. To cope with the large amount of generated data, needed resolution, and complex extraction of information, computer-based interpretation schemes were employed.

5. This report describes the procedures and documents the results of various seismic surveying methods that were used to try to detect and delineate cavities at the Medford Cave site in Florida. The seismic techniques employed were surface refraction, constant spacing, fan-shooting, surface shear wave, uphole refraction, and crosshole. Seismic investigations were not conducted at the Manatee Springs site because of a prohibition on the use of explosives in the State Park where the site is located.

PART II: SITE DESCRIPTION

Location

6. The Medford Cave site is located in Marion County, Fla., approximately 26 miles* south of Gainesville and 12 miles north of Ocala, as shown in Figure 1. More specifically, the site is situated 0.6 miles south of Reddick, Fla., and lies 500 ft west of old U. S. Highway 441 as presented in the U. S. Geological Survey map (1968) (Figure 2). The topography of the site and surrounding area exhibits a gently rolling surface. Vegetation consists of pasture grass covering approximately one-third of the site and all of the surrounding area. Tall trees cover the main part of the site.

Prior Scientific Use

7. Scientific use of the site began in the early 1970's when the Southwest Research Institute (SwRI), San Antonio, Tex., with the assistance of the Florida Department of Transportation (DOT), Gainesville, selected the site for evaluation of geophysical methods for cavity detection. In addition to mapping the cavity system (shown in Figure 3), the investigators conducted gravity, surface ground-penetrating "radar" (electromagnetic), and resistivity surveys (Fountain, Herzig, and Owen, 1975). All of the methods indicated anomalies at the site, with the results of the pole-dipole resistivity surveys considered the most definitive. The radar method was apparently limited to detection depths shallower than about 15 ft. The gravity survey results indicated anomalies which were relatively close to the largest known cavity room. Only three verification borings were placed at the site, with each boring in an area where at least two of the methods indicated anomalies. However, all + ee borings encountered only solid material to depths of 32 to 52 ft.

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* A table of conversion factors for converting U. S. customary units of measurement to metric (SI) units is given on page 3.

Site Selection Activity

8. Numerous U. S. Army Corps of Engineers personnel and others were contacted for assistance in locating potential sites for use in this research program. Generalized criteria for a suitable site were given as follows:

- a. The site should be owned by agencies or individuals who would approve geophysical testing to include drilling and explosive operations.
- b. The site should be easily accessible to personnel and equipment.
- c. The topography should be relatively level with only a few feet of overburden.
- d. The site should exhibit cavities with various sizes (mean diameters of approximately 2 to 20 ft) and depths below the ground surface (approximately 10 to 50 ft).
- e. The cavities should be accurately mapped.

9. After assessing information obtained from individuals contacted, it was decided that a reconnaissance trip to the Medford Cave site and to sites in the Daniel Boone National Forest, Ky., should be made. WES personnel visited these sites in March 1979 and chose the Medford Cave site based on the following factors which almost totally met the criteria for a suitable site:

- a. Cavity system nearly entirely air-filled.
- b. Easy site access for personnel and equipment.
- c. Gently sloping topography.
- d. Wide range of cavity sizes.
- e. Known portion of cavity system shallow, but with a good range of cavity depths.
- f. Cavity system apparently well mapped.
- g. Available results of previous geophysical tests at the site.

Personnel of the Florida DOT and SwRI had suggested this site as a candidate and during the visit, DOT acted as an escort, agreed to obtain site access permission, and assisted in the test program, particularly in drilling operations, which began in May 1979.

Geology

Area

10. The Medford Cave site is situated near the east-central flank of the Ocala uplift, a northwest-southeast trending "anticlinal structure" (Faulkner, 1970). Although the uplift is apparently bounded by faults, the area is considered tectonically stable. The primary active geological process affecting the area is solutioning of limestones and dolomites to produce karst topography with little surface drainage, development of subsurface cavities, sinkhole formation, etc. Local relief in the area is about 110 ft and consists of gently rolling hills and valleys. Generally the hills are capped by only a few feet of sands and clays over limestone. The shallow depth to top of limestone has resulted in many limestone quarries in the area. Extensive cave systems with attendant sinkhole formation are commonly associated with the hills and higher limestone elevations. The general geology of the area and of the Medford Cave site in particular is covered in a report by William D. Reves (1979) and is included as Appendix A in Butler (1983).

Site

11. The general sequence of materials at the Medford Cave site is sand (with silt, clay, and organic material), clay (may or may not be present at a given location), and limestone. Typically, the sand ranges from 0.3 to 3 ft in thickness. The clay occurs primarily in pockets in the limestone surface; therefore, the limestone is pinnacled. Two limestone formations are encountered at the site: (a) the basal limestone member of the Hawthorne formation (Miocene) is a hard, molluscan limestone (about 3 ft thick) which partially "caps" the hill under which the Medford Cave system is developed, and (b) the Crystal River formation (formerly known as the Ocala Limestone) of the Ocala Group of limestones (Eocene), which unconformably underlies the Hawthorne formation, is a soft to very soft, friable limestone (in many instances, the Crystal River Limestone is composed almost entirely of tests of

foraminifera and could be classed as a microcoquina). The known portions of the Medford Cave system are developed in the Crystal River formation.

The Medford Cave System

12. Figure 3 is the map of the Medford Cave system produced through the joint efforts of SwRI and the Florida DOT. Note the two portions of the cavity system; connection between the two portions is suggested, but no direct connection has been confirmed. Access to various parts of the system is by openings in the bottom or sides of three of the four sinks at the site, such as the Primary Entrance shown in Figure 3. Depths to top of the cave system range from 10 ft to as much as 45 ft. Segments of the cavity system vary in size up to a mean cross-section diameter of about 20 ft. Two of the "big rooms" of the system have unobstructed lengths of 45 ft or greater. The cavity system is air-filled with the top of the water table about 65 ft deeper than the deepest mapped cave level.

13. There are two major trends to the main part of the cavity system: N45°W and N70°E. The first trend above is approximately parallel to the axis of the Ocala uplift. The second trend is roughly the same as a mapped fracture (joint) trend through the Big Room. These observations are consistent with the general observation that cavity systems in Florida tend to develop along fracture (joint) trends (Faulkner, 1970).

14. The Medford Cave system is young and has no cave formations, although some limestone surfaces have a very thin calcite coating. There are petromorphs in the form of chert protrusions from the cave walls, and there are large rockfalls from the roofs of the two "big rooms."

PART III: FIELD INVESTIGATION

Site Grid System and Topographic Survey

15. In planning the site grid system, use was made of a surface benchmark established by the SwRI in their work at the site and also the center of the top rung of the step ladder in the Primary Entrance. These references allow the present grid system to "tie-in" to the subsurface with the results of the SwRI work at the site if desired.

16. The basic grid system established consists of N-S and E-W lines with survey reference markers every 20 ft. Over a substantial portion of the site, intermediate positions were also located (i.e., every 10 ft). At every survey position a 2- by 2- by 12-in. stake was driven flush with the ground surface, and every 20 ft an offset reference survey stake was placed and labeled with north and west coordinate locations. Station (0,0) is the southeastern corner of the survey grid, and sta (260,260) is the northwestern corner.* Figure 4 shows the survey grid relative to the cavity system. The four easternmost N-S survey lines as well as the northernmost E-W survey line were set with transit and tape with great care. The remainder of the grid was established with tapes and chaining pins. Station (0,0) was assigned a mean sea level (msl) elevation of 150 ft. The relative elevations of the top of each of the 2- by 2-in. stakes were determined to 0.01 ft by a level survey; a rod level was used to ensure verticality of survey rod at time of reading.

17. Figure 5 is the resulting topographic map for the site, where the contour interval is 1 ft. Although contours are drawn within the Entrance Sink and Dump Sink, the actual elevations are not well defined in the sinks. The topography approximates an inclined plane dipping from NW to SE.

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* For reference, the survey area is 6280 m^2 or 1.55 acres.

Drilling Program

Drilling phases

18. Drilling at the site was accomplished in three phases and for different objectives. The locations of all borings are shown in Figure 6. The initial phase of drilling consisted of borings C-1 through C-10 (drilled by Florida DOT but some would not stay open) and C-1A through C-5A and C-9A (drilled by WES), with the objective being to make boreholes for subsurface geophysical surveys. The second phase of drilling consisted of borings E-1 through E-16 with the objective being to obtain a detailed geologic cross section along a N-S line at the site. E-1 through E-16 were typically 25 to 33 ft in depth and spaced every 10 ft along the 80W line. Borings E-17 through E-25, the third phase, were verification borings placed to investigate geophysical anomalies.

Results

19. All borings except C-4A, C-1 through C-5, C-8, and C-10 were cored and logged. The core logs are presented in Appendix B (Butler, 1983) in this series. At boring C-7, soil samples were obtained and Figure 7 presents the results of density and water content tests. Figure 7 presents the airdried densities of limestone samples from boring C-6. Note that in the 30- to 40-ft-depth range, either cavities or soft zones were encountered in borings C-6 through C-9, which accounts for the low densities of samples from this zone.

20. Results of the second phase of drilling (E-1 through E-16) were used to prepare the detailed geologic cross section shown in Figure 8. Note the limestone pinnacles and clay pockets in the northern portion of the section. Zones of chert, commonly with large limestone-filled porosity, as much as 1.5 ft thick are encountered in several borings; and the chert commonly occurs just above a cavity or zone with little or no core recovery. Five definite tool drops occurred along the section, the largest being about 3 ft (boring E-9 at 22- to 25-ft depth), although numerous zones were encountered where the rock was very soft and

little or no core was recovered. Some of these very soft zones may have been clay-filled cavities.

Seismic Methodology

21. Six seismic techniques were employed at the Medford Cave site in an effort to detect and delineate cavity features. A list of these methods is given below:

- a. Surface refraction seismic.
- b. Constant spacing.
- c. Fan-shooting.
- d. Surface shear wave.
- e. Uphole refraction (wave front).
- f. Crosshole seismic.

The following sections of this report will deal with the specifics of each technique such as test procedure, results, data interpretation, and correlation with geologic conditions. It will be noted that other seismic methods such as the surface vibratory test are not addressed in this report because of the nonavailability of the proper equipment or the inability to obtain the desired expertise for conduct of the tests during the period of study.

Equipment and Test Procedures

Surface refraction seismic surveys

22. These tests were performed using a battery-operated, 24-channel seismograph and oscillograph. Operating speed of the oscillograph was about 35 ips with timing lines being displayed on the oscillogram at 10-msec intervals. Resolution time of data obtained from the instrumentation and test procedure was approximately 0.5 msec. Detonation of explosives (in shotholes 3 ft deep) provided the seismic energy source with charge sizes ranging from 0.25 to 0.5 lb. Response of the site materials was monitored by vertical, velocity-type transducers (geophones).

23. In practice, 24 geophones were employed for the seismic tests. Geophone intervals of 5 and 10 ft were used with the length of the seismic line dictating which spacing to use. The geophones were placed in a straight line along the surface of the ground with explosives being detonated at one end of the line and then the other, which resulted in a forward and reverse traverse. From this procedure, data were obtained for determination of apparent and true velocities and depths to refracting interfaces for examination for anomalies which may be cavity-related.

Constant-spacing tests

24. These tests were conducted using a battery-operated, single-channel enhancement seismograph and strip-chart recorder. The seismic unit was 0.25 msec. A 16-lb sledgehammer provided the seismic energy source. Generated seismic signals were detected using one vertical geophone.

25. The procedure employed for these tests consisted of placing the geophone at a selected location and striking a metal plate with the sledgehammer to provide the seismic energy. A distance of 50 ft was maintained between source and detector for one test and 25 ft for the other tests. Since the seismic unit was capable of enhancement, the metal plate was struck three times at the same position to obtain a reasonable signal amplitude. Amplifier gain was not changed during the tests. After a recording was made, the seismic source and geophone were each moved 5 ft, thus maintaining the 50- or 25-ft source-to-detector spacing. This procedure was repeated until the desired area was covered.

Fan-shooting technique

26. The 24-channel seismograph and oscillograph that were used for the refraction seismic tests were also employed in the conduct of the fan-shooting technique. Oscillograph speed and data resolution time were also the same. Detonation of explosives (in shotholes 3 ft deep) provided the seismic energy with charge sizes being about 0.25 lb. Detection of the seismic signal was accomplished by vertical geophones.

27. The test procedure consisted of placing 24 geophones at intervals of 5 and 10 ft on the arc of a circle at a radius of 70 ft from the seismic source. An explosive charge was then detonated and the resulting seismic signal recorded. This procedure was repeated four times with the geophones and source moved 14 ft each time. It will be noted that the first setup was not over a known cavity, but each succeeding setup covered varying size cavity features. In this technique, first-arrival time data are recorded at each geophone and all times should be equal unless geologic conditions between source and receivers vary substantially.

Surface shear-wave tests

28. These tests were conducted using the 24-channel seismograph and oscillograph that were employed for the refraction seismic tests. The energy source was provided by a 16-lb sledgehammer. Twelve horizontal geophones detected the generated seismic signal.

29. Since the desired length of shear- (S-) wave line and geophone spacings (5 ft) required more than 12 geophones, the lines were divided into two segments. This procedure is explained in Appendix B, EM 1110-1-1802 (Headquarters, Department of the Army, 1979). The geophones were placed in a straight line along the ground surface with the operational axis oriented perpendicular to the S-wave line. A rectangular wooden plank was then placed at one end of the line with the long axis oriented perpendicular to the line. The plank was then struck on one end and then the other with the sledgehammer. This produced seismic records each having a horizontally polarized S-wave signal which was 180 deg out-of-phase, thus providing positive identification of the S-wave arrival. The plank was then moved to the other end of the total S-wave line and again hit on the two ends with the sledgehammer which resulted in a forward and reverse S-wave line. Apparent and true velocities and depths to refracting interfaces can then be determined from formulas given in Appendix B, EM 1110-1-1802 (Headquarters, Department of the Army, 1979). The data obtained and the results above can then be examined for anomalies that may be cavity-oriented.

Uphole refraction survey

30. The 24-channel seismograph and oscillograph were also used in the conduct of this survey. The seismic source consisted of explosive charges (approximately 0.25 lb). The seismic signal was monitored by vertical geophones.

31. The test procedure is explained in Appendix E, EM 1110-1-1802 (Headquarters, Department of the Army, 1979). Twenty-four geophones were spaced 5 ft apart and extended away from the seismic source borehole in opposite directions. Detonation of charges were at 5-ft intervals beginning at the bottom of the boring (55 ft depth) and extending to the ground surface. Data reduction and analysis procedures are also given in Appendix E, EM 1110-1-1802 (Headquarters, Department of the Army, 1979) and by Franklin (1980).

Crosshole seismic tests

32. The 24-channel seismic unit and oscillograph were again used to record data from these tests. Exploding bridgewire (EBW) detonators provided the energy source to obtain compression- (P-) wave data and a surface vibrator connected by rods to a geophone that is sidewall clamped in a borehole provided the S-wave energy source. Geophones used to detect the seismic signals consisted of a triaxial array of transducers attached to an air-inflatable rubber bladder to provide a means for assuring sound contact with the walls of the boring.

33. The crosshole test procedure to obtain P- and S-wave data is described in Appendix E, EM 1110-1-1802 (Headquarters, Department of the Army, 1979). Source and receiver locations for each test were generally at the same elevation. Tests were performed at 5-ft-depth intervals in the boreholes. Deviation surveys to determine the vertical alignment of the borings were made by personnel of SwRI. Data reduction and interpretation techniques for determining true velocities and interface depths are described in Appendix E, EM 1110-1-1802 (Headquarters, Department of the Army, 1979). In addition to obtaining the above parameters, the data were examined for anomalous features that may be cavity-oriented.

PART IV: ANALYSIS AND DISCUSSION OF RESULTS

Surface Refraction Seismic Surveys

34. Eight refraction seismic lines (18 traverses) were run at the site. The traverses, designated S-1 through S-18, were oriented and located as shown in Figure 9. The selection of these locations was designed to investigate areas where no known cavities exist and areas within various size known cavity features. This would provide a quantitative assessment of detection-delineation at the site using the refraction technique. Three of the seismic lines were 240 ft in length and designed to determine whether deeper refractors were present at the site. Five of the seismic lines were 120 ft in length and were run to obtain detailed data over known cavity features.

35. Data from the refraction seismic tests were plotted as P-wave arrival time versus distance. These plots, along with apparent and true velocities and depths to refracting interfaces, are shown in Figures 10-17. It will be noted that cavity features have been superimposed on the plots when the seismic lines crossed a known cavity. Generally, two and three P-wave velocity layers were interpreted from the data. The near-surface zone had a wide range of velocities varying from 800 to 2500 fps with a thickness variation of 1.0 to 9.0 ft. From the seismic traverses that indicated three zones, the second zone exhibited velocities ranging from 3000 to 3335 fps with a thickness variation of 6 to 22 ft. The deepest zone for the two- and three-layer cases ranged from 4810 to 7650 fps which is indicative of the variability in competence of the limestone at the site.

36. As will be noted, anomalous data, in the form of delayed and early arrival times (and occasionally no discernible arrival at all) are present in the figures. These data are not all cavity-related, but are the result of the very complex geological conditions that exist at the site. Anomalous data that are cavity-oriented are shown in Figure 12.

37. As shown by Figure 12, the delayed arrival time toward the end of traverse S-6 correlates well with the cavity features (16 ft high by 11 ft wide and 6 to 11 ft high by 31 ft wide with the roofs approximately 11 ft below ground surface) shown. On the reverse from traverse S-5, there is no indication of delayed arrival times in the area of the cavities. This results because the shotpoint for traverse S-5 is sufficiently near the cavities that the P-wave travels along the surface of the rock over the cavities, thus producing no delay times. However, the P-wave from the shot for traverse S-6 has sufficient distance to bend or propagate along a path that is deeper than for S-5 (at the cavity locations) and therefore travels through or around the cavities producing the delay times noted on S-6. As seen, delay times are also present toward the end of traverse S-5, but these are caused by an increase in overburden and/or weathered rock (computed to be 17 ft near the shotpoint for traverse S-6 and shown to be 18 ft from boring data at coordinate 260 in Figure 8). Distance between shotpoint 6 and the boring data is 37 ft.

38. Most of the anomalous data present in the other figures can be accounted for by interpreting the data from the forward and reverse traverses and being able to correlate the results with geologic conditions along the traverses. However, some of the data (even one arrival time) could well be cavity-related, but no plausible interpretation can be made to substantiate this possibility. The following discussion will address the major anomalies shown in the figures and their correlation with known geologic conditions. Figure 10 indicates that anomalous data in the form of early arrival times are present on traverses S-1 and S-2 starting at about 50 ft from the beginning of S-1 and extending to about 140 ft. These early arrivals are caused by the 5150-fps rock becoming closer to ground surface in the above distance range as substantiated by data from borings E-19 to E-22 (locations shown in Figure 9) which indicate soft to medium hard limestone at about 2 ft below ground surface. At a distance of 150 ft from the start of traverse S-1, anomalous data (delayed arrival times) appear on traverse S-1 to a distance of 240 ft. These times are attributed to a near vertical down-dip of the 5150-fps rock (computed to be 24 ft near the start of traverse S-2). The data

from traverses S-3 and S-4 (Figure 11) resemble those from traverses S-1 and S-2 as regards anomalies. The early arrival times shown between a 60- and 120-ft distance from traverse S-3 are probably indicative of the 5890-fps rock becoming closer to ground surface. Boring data from E-25 and E-11 (locations shown in Figure 9) indicate limestone to be 9 and 6 ft, respectively, below the ground surface, which adds credence to the statement that the early arrival times result from the closeness of the limestone to the ground surface. The delayed arrival times toward the end of traverse S-3 (200- to 240-ft distance) are due to a near vertical down-dip of the 5890-fps rock, which is verified by the increased depth to the 5890-fps layer (computed to be 25 ft near the start of traverse S-4).

39. Early arrival time data are noted from a 40- to 70-ft distance from traverse S-9 (Figure 14). Boring C-2A data (40 ft from and offset 7 ft north of the start of traverse S-9) indicate limestone to be 2 ft below ground surface; therefore, the early arrivals are probably due to the 7420-fps rock being closer to ground surface. The delayed arrival times toward the end of traverse S-9 are caused by the P-wave propagating through a slower velocity (1000 fps) and deeper overburden (6 ft) than at the beginning of traverse S-9. Data from traverses S-11 and S-12 (Figure 15) indicate an anomalous zone at a 60- to 85-ft distance from traverse S-11 in the form of delayed arrival times. These arrival times are caused by a soil-filled depression in the 6160-fps rock, which is substantiated by data from boring E-25 (located 85 ft from the start of S-11 and offset 6 ft north) showing 9 ft of sand and clay overburden to be present. Early arrival times are noted at distances of about 25 to 80 ft from the beginning of traverse S-13 (Figure 16). Again, these early arrivals are interpreted to be due to the rock (4810-fps velocity) becoming closer to the ground surface as in the cases of the early arrival times noted in previously discussed traverses. However, no boring or other data in the anomalous area verify the interpretation.

40. Figure 17 indicated delayed times at distances of 25 and 30 ft from the beginning of traverse S-15. These times are believed due

to a lower velocity near-surface material or a depression in the 6500-fps rock in the proximity of the distances above, but no data are available to verify the interpretation. At distances of 50 to 65 ft and 85 to 95 ft, early arrival times are noted on traverses S-15, S-17, and S-18. These data are caused by the 6500-fps rock becoming closer to the surface as shown in the geologic profile (Figure 8) from coordinates 105 to 120 and 140 to 150 ft. The dalay time anomalies at the end of traverses S-15 and S-17 are due to the clay pocket or depression in the limestone shown from coordinates 160 to 180 in Figure 8. Therefore, this leaves only one seismic line out of seven that actually ran across known cavity features that successfully detected a cavity. This represents about a 15 percent chance of detecting a cavity given the geological conditions present at this site. If subsurface geology at a site is such that a higher velocity refractor were present beneath the cavity system, then chances of detection would have been enhanced to some degree since delay times should be produced by wave propagation through or around the cavity.

41. Delineation of the cavities shown in Figure 12 would appear to be good if only the anomalous data (delayed arrival times) were considered since these would tend to indicate cavities existing the full distance that delay times were observed. However, there is a distance of 37 ft between known cavities, and a boring drilled in this area would not intersect a cavity unless the two cavities are interconnected. This leads to the conclusion that if two or more cavities not presently known are in proximity, chances of total planar delineation will be nil. Chances of defining the start of the system should be good. If only one cavity is involved, total planar delineation should be within one to two geophone spacings.

Constant-spacing Surveys

42. Three tests were conducted employing this technique, the locations of which are shown for tests 1 and 2 in Figure 18 and test 3 in Figure 19. Test 1 was performed north to south along the 80W line at

5-ft intervals while maintaining a source-to-receiver distance of 50 ft. Test 2 was conducted northwest to southeast across an extension of the cavity system near the west entrance at 5-ft intervals while maintaining a 25-ft source-to-receiver spacing. Test 3 was conducted perpendicular to test 2; i.e., a 25-ft source-to-receiver distance was maintained southwest-northeast while moving the source and receiver at 5-ft intervals from northwest to southeast. The 25- and 50-ft source-to-receiver distances were chosen based on the "rule-of-thumb" for refraction seismic surveys; i.e., the length of the line should be about three times the desired depth of investigation. The cavity features of interest in these tests ranged from 9 to 20 ft deep. These tests were performed to obtain data so that the entire seismic signal could be examined for anomalous features which may be cavity-related. Of primary interest was frequency, amplitude, and wave shape of the signal resulting from the presence and absence of cavity features.

43. The oscillograms obtained from test 1 were digitized and the data are presented in an amplitude (digitizer units)-time domain as shown in Figures 20-37 for position 0 ft (source and receiver coordinates of 260,80 and 210,80, respectively) through 170 ft (source and receiver coordinates of 90,80 and 40,80, respectively). These data are portrayed to provide a general overview of signal amplitude and frequency as a function of time and for examination of the character of the wave form.

44. After studying the digitized data for the various positions, several generalized observations were made. It appeared that the data from positions 0 to 40 and 80 to 90 exhibit larger amplitudes, lower frequencies, and more uniform (sinusoidal without jaggedness) wave shapes than the data from positions 45 to 75 and 95 to 165. The locations of the above positions were plotted on the geologic profile along the 80W line and are shown in Figure 38. It will be noted that positions 45 to 85 and 95 to 165 are almost centered over the known cavities while only the last 20 ft of positions 0 to 40 and the last 5 ft of positions 80 to 90 overlie cavities.

45. To make a more detailed interpretation of the digitized data presented in Figures 20-37, a frequency spectrum analysis was performed.

The results of this analysis in the form of linear spectral density (amplitude versus frequency) are presented for each position in Figures 39-44. The data for positions 0 to 40 ft indicate a relatively broad frequency band from lows of 15 to 20 Hz to highs of 120 to 130 Hz with a very pronounced predominant frequency in the 50- to 60-Hz range. Amplitudes in the predominant frequency range vary from about 8 to 15 units. From positions 45 to 75 ft, there is a trend toward higher frequency data (extending to 170 Hz) with the predominant frequency being in the 70- to 80-Hz range. It is particularly noteworthy that amplitudes in this position range do not exceed 8 units except for position 45 ft which is approximately 10 units. Lowest amplitudes (approximately 5 units) are noted from positions 55 to 65 which nearly centers on the two cavity locations detected from exploratory borings E-8 and E-9 (Figure 38). Positions 80 to 90 ft indicate a return to the predominant frequency range of 50 to 60 Hz and a considerable dissipation of the higher frequencies. Amplitudes increased to a 7.5 to 15+ unit range. This area is virtually clear of known cavities with only the last 5 ft of position 90 over a cavity. From position 95 to 165, there is a significant increase in higher frequency data (to about 170 Hz). The predominant frequency varies greatly for these positions (60 to 110 Hz). Amplitudes show a marked decrease in this area, varying from 2.5 to about 9 units. Except for positions 95, 100, and 150 ft, amplitudes would range from 2.5 to 5 units. Lowest amplitude (2.5 units) observed was for position 130 ft, which was centered over the two known mapped cavities.

46. It may be expected that the higher frequency data are attributable to the increasing closeness of the rock to the ground surface and the absence of clay from position 95 to 165 ft, but the low amplitude data, particularly from position 105 to 130 ft, which nearly centers on the cavities, lend credence to these data being cavity-related.

47. In an attempt to alleviate the subjective observations and interpretations discussed in the last three paragraphs, the area under the digitizer units versus frequency curve for each position was computed and the mean frequency calculated. The area and mean frequency for

each position was then plotted versus the midpoint of the position. Since each position covered 50 ft of ground surface, it appeared more meaningful to plot the area and mean frequency at the midpoint of the position. The resulting plots along with the locations of the known cavities are shown in Figure 45.

48. Since the observations and analyses thus far suggest that low amplitudes coupled with high frequencies are cavity-related, it appeared feasible to establish datums for the frequency and area data. Values above these datums would signify high frequencies and large area, and values below the datums would be low frequencies and small area. The frequency datum was established by adding the three lowest and three highest values and determining the average. The datum for the area was done in this same manner. Frequency and area datums of 98 Hz and 555 unit Hz were determined and are shown by the dashed lines in Figure 45.

49. Referring to Figure 45, the analysis techniques presented have alleviated much of the subjectiveness but definitely not all. The most definitive data are from the center of positions 110 to 145 where the areas are very small and the frequencies substantially high. As seen, the above position midpoints virtually center over the two known mapped cavity features, which tends to substantiate the concept that low amplitudes coupled with high frequencies are cavity-related. Some argument could be made that the data show indications of the cavities detected from exploratory borings E-8 and E-9, but subjective judgment would again be interjected.

50. Test 2 which was conducted near the west entrance of the cavity system (Figure 18) consisted of 13 positions with position 0 having the source at 0 ft and the receiver at -25 ft while position 13 had the source at 60 ft and the receiver at 35 ft. The oscillograms obtained for the 13 positions are shown in Figure 46. Although the data from this test were not subjected to the analysis techniques performed on the test 1 data, the oscillograms are presented to aid a geophysicist employing the constant-spacing technique in karstic topography to be

cognizant of field data that suggest cavity features. If a cavity is suspected, then additional tests in the anomalous area would be beneficial.

51. Referring to Figure 46, the data shown for positions 0 to 25 ft indicate relatively clean signals, although some of the wave forms do have a certain amount of distortion. Predominant frequency of the signals appear to be generally in the 50- to 60-Hz range, although higher frequencies (90 to 120 Hz) are indicated from the data at position 25. Amplitudes of the signals in this area are very strong as evidenced by the saturated signals at every position. From positions 30 to 45 ft, the wave form is very distorted as higher frequency data appear. Amplitudes indicate a severe reduction from those at positions 0 to 25 ft and almost dissipate at positions 30 and 45 ft. As is noted in Figures 18 and 46, the source location for position 30 ft is located directly over the cavity extension and positions 35 to 50 ft span the cavity with source and receiver. Positions 50 to 60 ft show a return to the lower frequency data with a predominant frequency range of about 55 to 65 Hz. Wave forms are still somewhat distorted especially at position 60 ft. Amplitudes in this area have become much stronger but not as high as at positions 0 to 25 ft.

52. The layout for test 3 which was conducted perpendicular to test 2 (Figure 18) consisted of nine positions (25 to 65) and is shown in Figure 19. The data obtained from test 3 are shown in the oscillograms (Figure 47). It is immediately evident that the amplitude at position 30 ft is virtually nil and from Figure 19, it is seen that the cavity extension underlies about one-half of this position. The wave form is barely discernible in Figure 47 but appears to have some distortions. Frequency content looks rather low but cannot be assessed. Positions 25, 35, 40, and 45 ft generally have distorted wave forms, and higher frequencies are attempting to interfere with the lower predominant frequency. Amplitudes are larger than for position 30 ft but are still quite low. For positions 50, 55, and 65 ft, the wave forms are virtually free from distortion, frequencies are in the 55- to 65-Hz range and signal amplitudes are very strong, probably indicating a return

to noncavity-related subsurface conditions. Position 60 ft indicates data that are interesting. The wave form is relatively clean, but there are only two periods before the data attenuates completely. The frequency of these periods is about 35 Hz, and the amplitude is somewhat low. Because of the peculiarity of the data at this position, it was decided that an exploratory boring should be drilled to ascertain the nature of the subsurface conditions. However, the selected location (on the position 60-ft line) for the boring could not be reached by the drill rig due to large trees in the vicinity. Therefore, the boring (E-24) was made as close as possible to the original location. The boring data from borehole E-24 are shown in Figure 48. If subsurface material conditions are the same at position 60 ft, the soft to very soft limestone with 4 and 5 percent core recovery and rock quality designation (RQD) of zero, is probably responsible for the seismic data obtained.

53. The results of the tests using the constant-spacing technique demonstrated that cavities can be detected and approximately delineated in plan. The two known, mapped cavities along the 80W line where test 1 was conducted were 4 ft wide by 5 ft high and 12 ft wide by 8 ft high and about 15 and 20 ft below ground surface. The cavities detected from borings E-8 and E-9 consisted of a 3-ft tool in each; therefore, the horizontal dimensions are not known. For tests 2 and 3, the cavity extension was 5 ft wide by 4 ft high and located 9 ft below ground surface. Detection of a cavity is possible by conducting a test in one direction. However, to assure detection of a feature, two tests should be conducted (perpendicular to each other) across the anomaly. As regards delineation in plan, detailed tests in at least two directions would be required using closely spaced position intervals. Even with close intervals, it may not be possible to delineate a feature in less than one source-to-receiver distance. For example, with a source-to-receiver distance of 50 ft and position intervals of 5 ft, it may take conducting the test at all 11 positions (0 through 10) which is actually one source-to-receiver distance to delineate the cavity. Delineation as regards depth to and height of the cavities was not determined. In

addition, since all the known cavities at the site were fairly shallow, the effect of cavity depth on detection success is not known. It will be noted that although two source-to-receiver distances (25 and 50 ft) were used with successful results, the effect of varying the source-to receiver distance for a given target is not known. As stated previously, the 25- and 50-ft source-to-receiver distances were chosen based on the "rule-of-thumb" for refraction seismic tests; i.e., the length of the line should be about three times the desired depth of investigation.

Seismic Fan Tests

54. The layout for the seismic fan tests is shown in Figure 49. As noted, there were five tests, each consisting of a source location and 24 geophone positions. The first setup had the seismic source (explosives) at coordinate 40,0 and the geophones spaced at 5- and 10-ft intervals on a 70-ft radius arc with the last setup having the source at coordinate 80,40 with the geophones again on a 70-ft radius arc. The 70-ft distance between source and receivers was selected based on the "rule-of-thumb" for refraction seismic tests; i.e., the length of line should be about three times the desired depth of investigation. Since the cavities in the test area ranged from about 15 to 25 ft deep, the 70-ft radius used in the tests was reasonable. These tests were designed to obtain first-arrival time data starting in an area of no known cavities and proceeding across locations of cavities on the premise that equal or near-equal arrival times would be obtained if geological conditions were the same over the investigated area. If anomalous data were indicated, then an assessment as to whether they were cavity-related would be possible.

55. The results of the fan tests, presented in plots of the P-wave arrival time versus geophone number, are shown in Figures 50-54 for tests 1 through 5, respectively. Observing the plot (Figure 50) for the data obtained from no known cavity area, the arrival times vary between 16 and 21 msec or a 5-msec band except at geophones 23 and 24

which exceeds this range. In fact, there is a strong increase in arrival time trend from geophones 10 to 24. It is known that boring E-21 (approximately in line between source and geophone 20) detected numerous small cavities from 10 to 40 ft deep, but is is also known that overburden (clay) thickness increases toward the east; therefore, no conclusion can be drawn relative to these data being cavity-oriented. Referring to the data from test 2 (Figure 51), all arrival times can be banded between 15 and 20 msec except for arrival times for geophones 10, 11, 23, and 24. Again there is a rising trend in times for geophones 20-24, which lends credence to the overburden thickness contributing to the increased times. The greatest times measured were for geophones 10 and 11 which were located at the spur (2 ft wide by 2 ft high) of the main cavity system (Figure 49). This feature is about 25 ft below ground surface. Therefore, these times could be cavity-related. Observing the data from test 3 (Figure 52) arrivals can be banded between 12.5 and 17.5 msce except the times for geophones 15, 23, and 24 which again indicate a strong increasing trend in time from geophones 22 to 24. The large arrival time for geophones 15 cannot be accounted for since subsurface conditions between source and receiver are not known. It will be noted that the arrivals at geophones 1 and and 9 to 13 (located over the cavity) do not indicate any anomalous times. The data from test 4 (Figure 53) indicate arrival times can be banded between 14 and 19 msec except for data obtained at geophones 19 and 20 which exceed the 5-msec range. It will also be noted that there is a definite increasing trend in the data from geophones 15 to 20. The data from refraction traverse S-10 (Figure 14) indicate an increase in overburden thickness in this area; therefore, the arrival times detected by geophones 15 to 20 probably reflect this condition. It is also seen that the arrival times at geophones 6 to 13, which were positioned over the cavity system, did not exhibit anomalous values. The data from fan test 5 are presented in Figure 54. All arrival times are between 11 and 16 msec except for the arrivals at geophones 20 and 21. These two locations are in the vicinity of refraction seismic traverse S-10 (Figure 14), which indicates an increase in overburden thickness. The arrival times detected by the geophones (4 to 14) over the cavity system exhibit no anomalous values.

56. In summary, the results of the fan tests present no conclusive evidence of anomalous arrival times being cavity-related. In fact, since no anomalous data were observed from geophones placed over large known cavities, it is almost certain that the suspicious arrivals (those which exceeded the 5-msec band) were related to increased overburden or velocity variations and not cavity features.

Surface Shear-wave Tests

57. Four shear-wave lines (eight traverses) were run at the site. These traverses, designated SS-7 through SS-14, were oriented as shown in Figure 55 and correspond to the same locations as refraction seismic traverses S-7 through S-14. The selection of these locations was designed to investigate areas with various size cavity features so that a quantitative assessment of detection-delineation could be made using this technique. All of the S-wave lines were 120 ft in length with 5-ft geophone spacings to obtain detailed data over known features.

58. During the conduct of the tests, it was evident that good, reliable S-wave data were not being obtained. There appeared to be a "ringing" effect of the signal much like attaining the resonant frequency of the geophone. This frequency was about 120 Hz and did not appreciably change during the record length. While it did appear that a reversal may have occurred after the start of data from records obtained for hammer blows to opposite ends of the plank, detailed examination in the office indicated that these apparent reversals were unreliable and were slight phase shifts in the signal rather than true S-wave arrivals. The reasons for the failure to obtain reliable S-wave data are not known, but failure is probably due to the energy content and repeatability of the input as well as coupling between source and ground surface (Franklin, 1979).

Uphole Refraction Survey

59. One uphole refraction test was run at the site along the 80W line as shown in the layout (Figure 56). This location was selected to obtain data over two cavity features that differed considerably in size as shown in the geologic profile (Figure 8). The premise followed was that at least one feature and hopefully both would be detected and delineated from this test. As noted in Figure 56, boring C-2 was used for the source or shothole with the geophones placed along the ground surface at 5-ft intervals. Explosive charges were detonated at 5-ft intervals starting at the bottom of boring C-2 (depth of 55 ft) and extending to ground surface with a record of P-wave velocities at the geophones being obtained for each shot.

60. Data from the uphole refraction test were contoured at 2-msec intervals with the resulting plot shown in the Meissner diagram (Figure 57). From the data in this diagram and refraction seismic traverses S-15 and S-18 (Figure 17), layer boundaries and velocities were determined which produced a two-layer system. The near-surface zone had a velocity of 1500 fps to a depth of 5 ft and was underlain by a 6500-fps layer. From these velocities and the first layer thickness, the travel times were computed and, consequently, a 2-msec contoured plot of these times for an ideal two-layer system was made and is shown in Figure 58. The computed travel times were subtracted from the measured travel times; i.e., values in Figure 58 were subtracted from data in Figure 57 to produce the contours in the anomaly diagram (Figure 59). The data in this diagram were examined for anomalous features that would be produced by a cavity such as the anomaly shown in Figure 60 which was calculated by Franklin (1980). From the contours in Figure 59, one may see that the contour pattern does not resemble the one produced by a large cavity (Figure 60). The contours in Figure 59 do become closely spaced toward the north, but the character of the contours approximates that for a depression in the rock surface and correlates well with a rock depression filled with clay as seen in the geologic profile (Figure 8) from coordinates 160 to 175. In

addition, it is expected that a P-wave propagating around or through a cavity would produce larger travel times than the computed times for an ideal two-layer case. Therefore, a cavity should produce positive anomaly contours. However, when the measured times were subtracted from the computed times and contoured, negative values for the contours were produced except at the north end of the anomaly diagram. Since the contour pattern produced by anomalies was not indicated and negative rather than positive contour values were produced, it is concluded that the cavities were not detected.

61. In summary, the results of the uphole refraction test did not indicate anomalous data similar to that expected to be produced by cavities; therefore, detection using this technique was not achieved. It may be said that the technique was not given a fair trial in that more tests were not conducted at other locations. However, when two cavity features (12 ft wide by 8 ft high and 4 ft wide by 5 ft high) spaced about 10 ft apart cannot be detected, then the chance of this technique detecting cavities appears very low.

Crosshole Seismic Tests

62. These tests were run at the locations shown in Figure 61. Borings C-10 (60 ft deep) and C-1 (45 ft deep) comprised one crosshole set and borings C-6 (51 ft deep), C-7 (59 ft deep), and C-8 (53 ft deep) constituted the second set. It will be noted that in Figure 61 the arrows point from the borehole used for the seismic source to the hole(s) used for the receiver(s). The locations selected were designed to investigate one area where no known, mapped cavities existed and another where a feature with known dimensions existed. This would provide a quantitative assessment of detection-delineation at the site using the crosshole technique. The tests were performed starting with source and receiver(s) at the bottom of the borings. Because of the difference in depths of the boreholes in each set, tests were not conducted until source and receiver could be located at the same depth at which time tests were performed at 5-ft increments until ground surface was reached.

63. Data obtained from the crosshole tests were the increments of time required for P- and S-waves to propagate from the source to a point of detection. These times were then divided into the distance between source and receiver(s) to provide apparent velocities from which a computer program for crosshole seismic interpretation could determine true velocities and depths to interfaces. The P-wave velocity results from the crosshole test conducted from borings C-10 to C-1 were interpreted to produce the profile shown in Figure 62. It will be noted that the cavity feature existing between the borings has been superimposed on the profile based on the 1974 mapping of the system. Observing Figure 62, it is evident that the lowest velocities (3595 and 4650 fps) were obtained in the cavity region. The 3595-fps velocity is also shown to exist about 2 ft below the cavity, but this velocity is almost certainly cavity-related due to an expansion of the dimensions, errors in mapping, or limitations in data reduction and interpretation. Regardless of the reason for the velocity, this cavity was detected and delineated within 2 ft in the vertical dimension. Velocities above and below the cavity range from 5115 to 7620 fps. The 7620-fps velocity probably was indicative of the more competent Hawthorne limestone formation that exists near the surface of this site.

64. The results of the P-wave crosshole test conducted from borings C-7 to C-6 and C-7 to C-8 were analyzed to produce the P-wave velocity profile shown in Figure 63. It will be noted that a plot of dry density versus depth obtained from limestone samples taken from C-6 is included in the figure. Also, there are two small cavities and a soft zone, all about 1 ft high, shown on the profile. The P-wave velocity from C-7 to C-6 indicates a variation of 5015 to 8880 fps. The lowest zone, 5015 fps, is evident from 36 to 46 ft deep and correlates well with the low densities (1.57 and 1.6 g/cm^3) obtained in this area. Likewise, higher velocities are seen to correlate well with larger densities. The small cavity noted in boring C-6 and the soft zone in boring C-7 do not appear to be interconnected since the velocities in this zone are relatively high. In summation, the 5015-fps zone is apparently a weak layer that extends from C-7 to C-6 or

could very well contain a cavity in between the borings. This zone is considered suspect and an intermediate position borehole would be justified to evaluate it.

65. The P-wave velocities determined from borings C-7 and C-8 exhibit a range from 3680 to 8370 fps. The lowest zone, 3680 fps, exists from a depth of 16 to 27 ft and is considered to be a prime candidate for the location of a cavity. This profile is almost a replica of the profile (Figure 62) from borings C-10 to C-1, where the 3595-fps zone was due to the presence of the cavity. Likewise, the 3680-fps zone would have to be considered as having a cavity present and should be drilled.

66. The crosshole S-wave tests did not produce valid data due to the inability to propagate certain frequencies easily through the subsurface materials. When a frequency did propagate, the gains of the amplifiers (54 to 66 db) were so high that noise masked the arrivals and made arrival time picks unreliable. When it appeared that an arrival could be determined, subsequent redundant records indicated the arrival times for what appeared to be similar events were different.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

67. Based on the results of the tests conducted using the various seismic techniques, the following conclusions were drawn:

a. Surface refraction seismic tests. There were many anomalies detected using the refraction seismic technique, but they could be explained knowing the geologic conditions at the site and being able to correlate data from the forward and reverse traverses. Only one seismic line out of seven that was run across known cavity features successfully detected a cavity. This one instance may have been a quirk of nature. If a cavity can be detected, planar delineation can be achieved within one to two geophone spacings if only one cavity is involved. If two or more cavities are in proximity, delineation of the start of the features was good. Total planar delineation would be nearly impossible.

b. Constant-spacing seismic tests. The results of the tests using the constant-spacing technique demonstrated that shallow cavities several feet in diameter can be detected and delineated. Features in the data that indicated the presence of a cavity were low amplitudes (small area) coupled with high frequencies and, to a lesser extent, signal distortion. To assure detection and delineation of a cavity feature, two tests should be conducted (perpendicular to each other) across the suspected anomaly using closely spaced position intervals. Even with close intervals, it may not be possible to delineate a feature in less than one source-to-receiver distance. Delineation as regards depth to and height of the cavities was not determined. In addition, since all the known cavities at the site were shallow (less than 30 ft), the effect of cavity depth on detection success is not known. Two source-to-receiver distances (25 and 50 ft) were used with successful results. The effect of varying the source-to-receiver distance for a given target is not known. The above distances were chosen on the basis of the "rule-of-thumb" for refraction seismic surveys; i.e., the length of the line should be about three times the desired depth of investigation.

c. Seismic fan tests. These results presented no conclusive evidence of anomalous data being cavity-related and no anomalous data were obtained when geophones were placed over known cavity features; therefore, the data anomalies from these tests were believed to be related to increased overburden or velocity variations and not to cavity features. Chances of cavity detection-delineation using this technique appear to be negligible.

d. Uphole refraction survey. The results of the uphole refraction test did not indicate anomalous data that should be produced by cavities; therefore, detection using this technique was not achieved. The sensitivity of the uphole refraction method to the presence of buried cavities is marginal, if travel times alone are used. These times are affected by the cavity features and large cavities are detectable, but with the degree of resolution normally attained by state-of-the-art instruments and field procedures, many cavities of a size great enough to be of engineering significance such as a 14-ft-wide tunnel are for practical purposes undetectable by means of the uphole refraction technique.

e. Crosshole seismic tests. The P-wave data obtained across a known cavity indicated significantly lower velocities in the cavity region than above or below this area. Delineation using the depth to and thickness of the low-velocity zone as a guide was within 2 ft of the cavity depth and height. The P-wave data obtained across an area of no known cavities produced two low-velocity zones. One of these anomalies was almost identical in velocity profile as the profile produced by the known cavity. Although it cannot be said that cavities produced the two low-velocity layers, anomalies of this type should be drilled. The crosshole seismic technique cannot detect a cavity, per se, but will identify weak zones or low-velocity layers that may or may not be void-related. Delineation of the low-velocity layers with this technique can be excellent but is subject to the limitations of the crosshole method such as borehole spacing, depth intervals used in the tests, and certain geological conditions such as low-velocity lenses or seams.

Recommendations

68. The constant-spacing seismic test is the only surface seismic testing procedure recommended for use in cavity detection and delineation. It appears to be a very successful method for locating cavities which are at depths of less than 30 ft and which have diameters in excess of 4 ft. The use of digital recording and i ld-automated data

processing techniques hold the potential for making the interpretation of cavity-related features relatively simple. The only subsurface method recommended is the crosshole P-wave velocity test which, while it requires boreholes, can significantly reduce (probably by a factor of 2), the number of boreholes necessary in investigations to locate large (at least a few feet in diameter) cavities.

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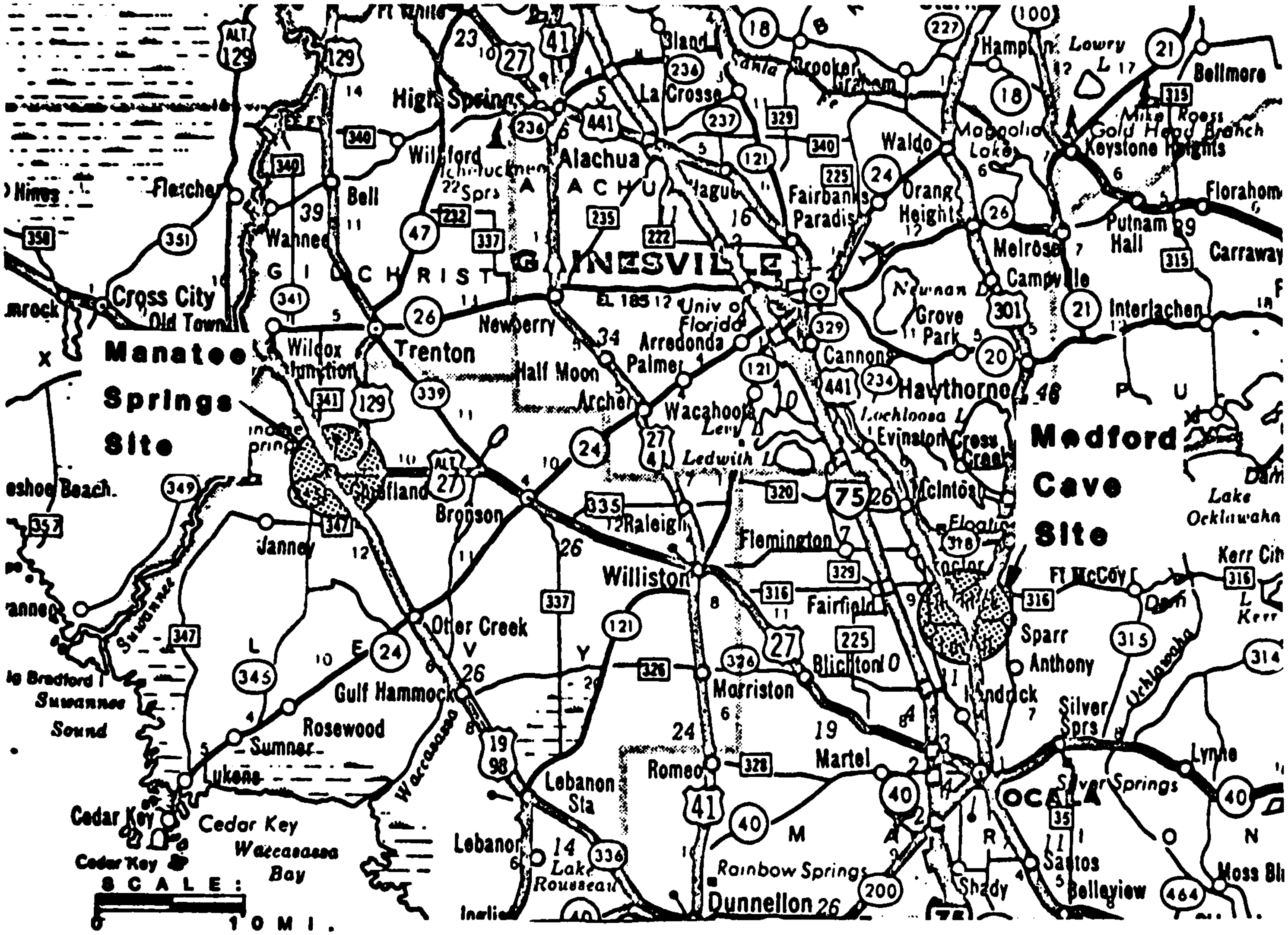


Figure 1. Map showing locations of Medford Cave and Manatee Springs test sites

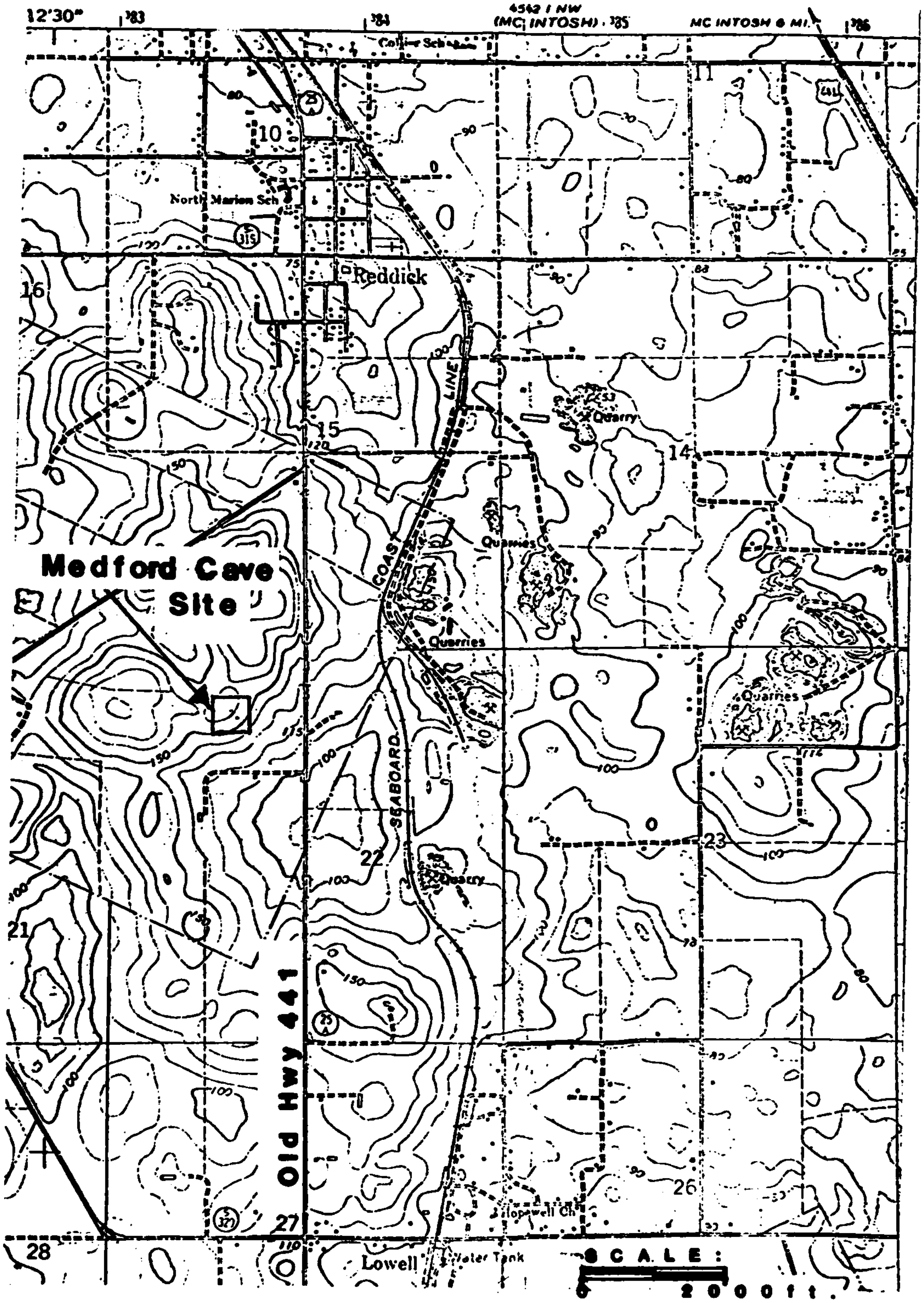


Figure 2. Portion of U. S. Geological Survey, Reddick, Fla., quadrangle sheet (1968) showing Medford Cave test site

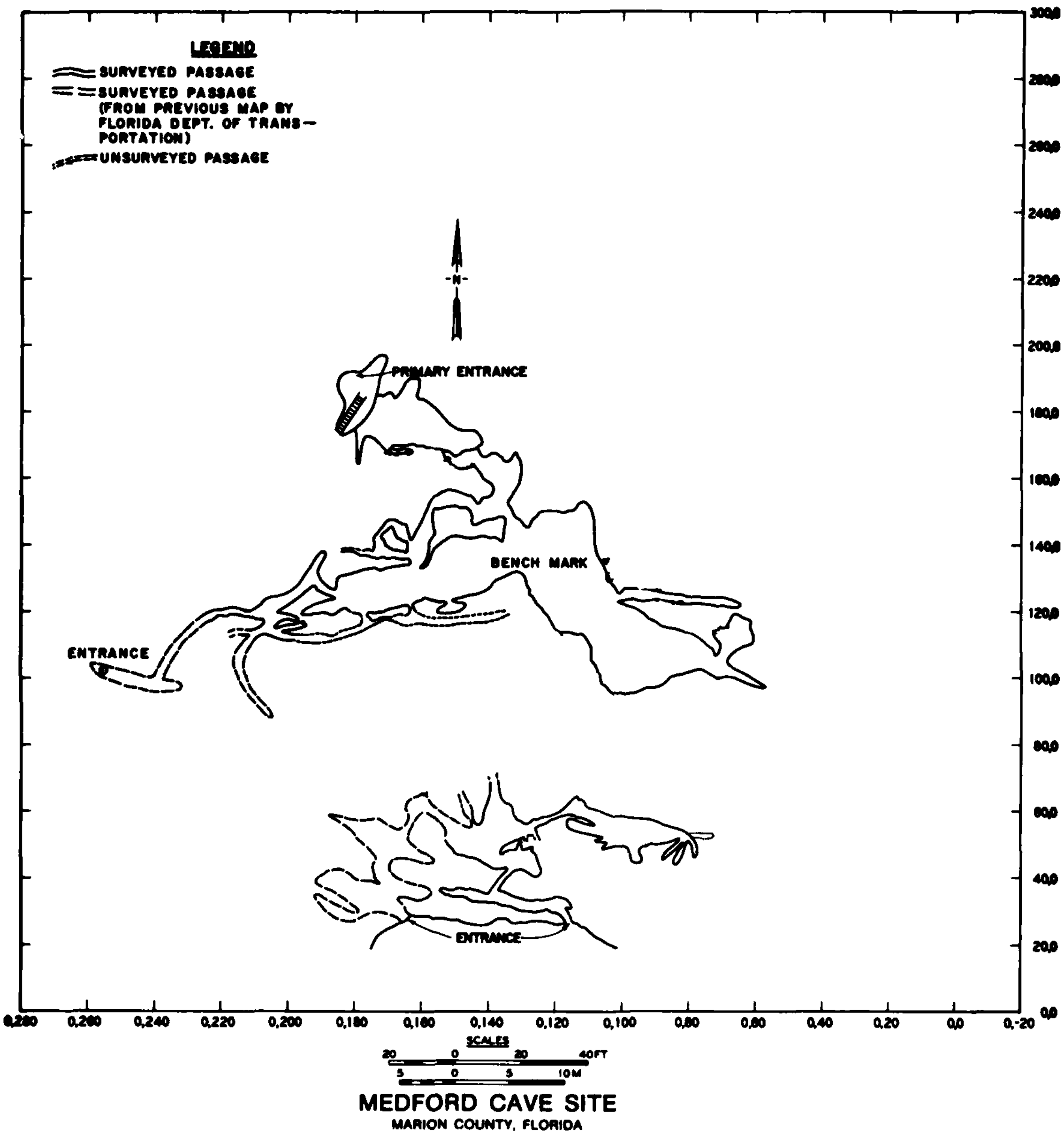


Figure 3. Plan view of cavity system

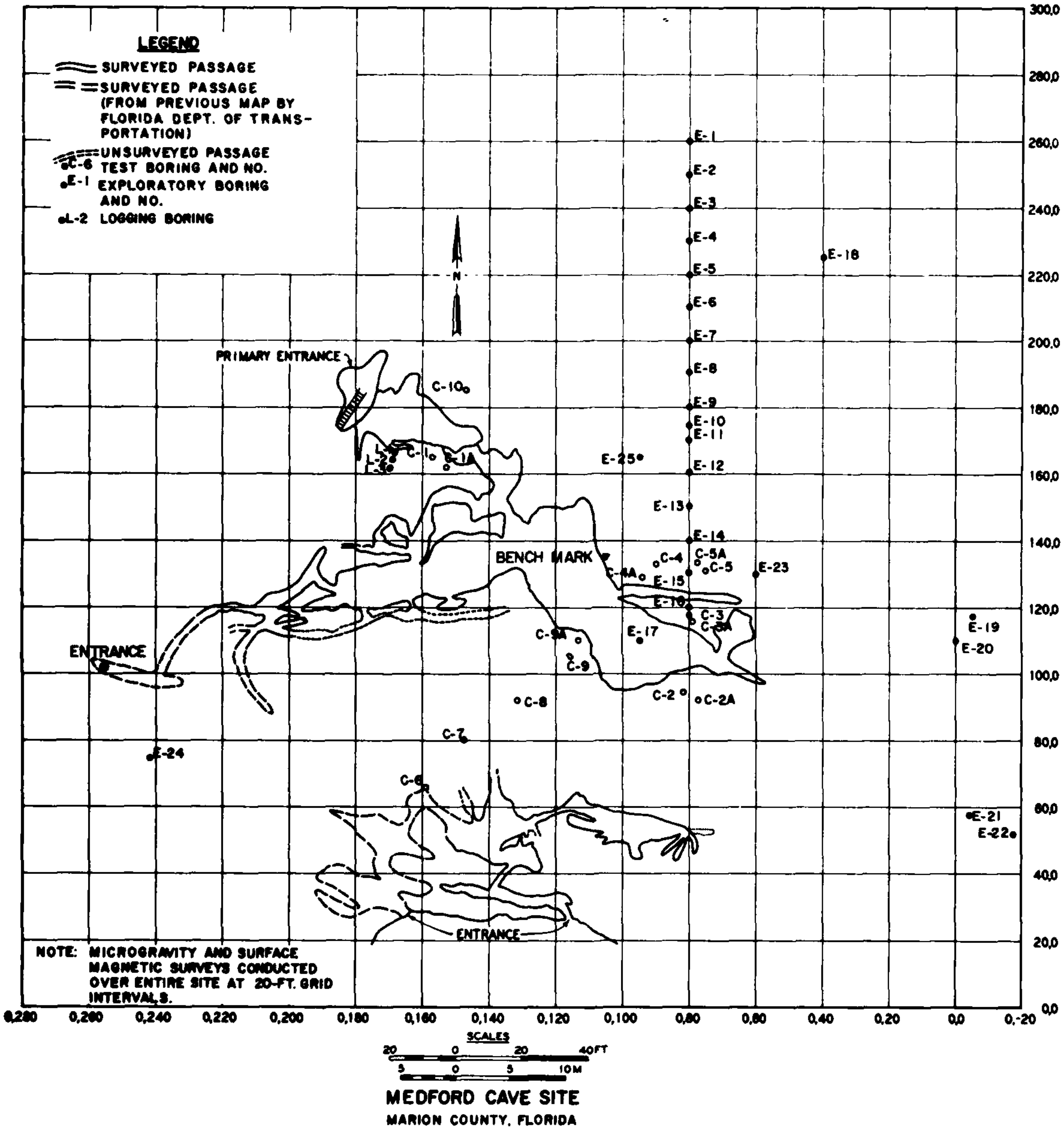
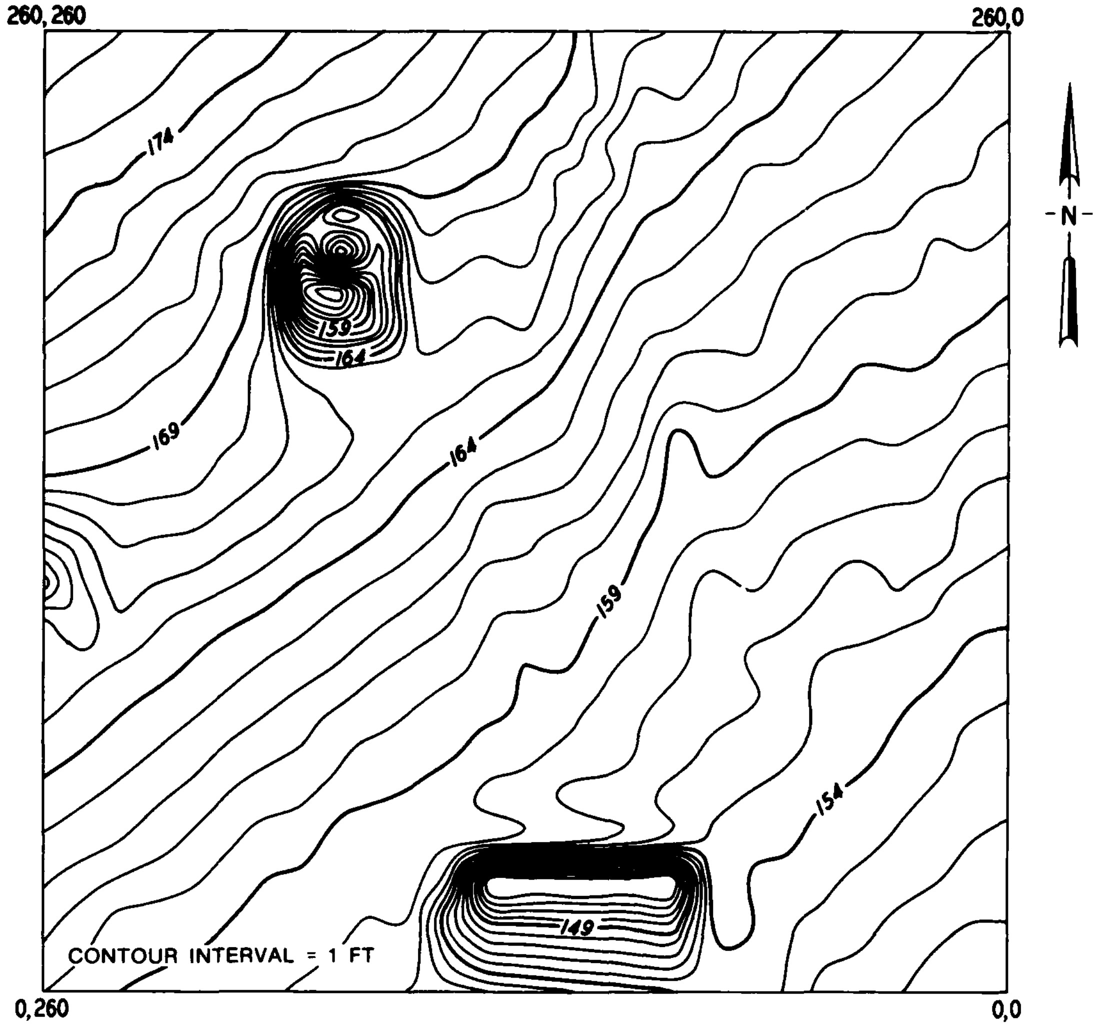


Figure 4. Map showing grid system established at site



SURVEYED PORTION OF
MEDFORD CAVE SITE, FL

Figure 5. Map showing surface topography at site

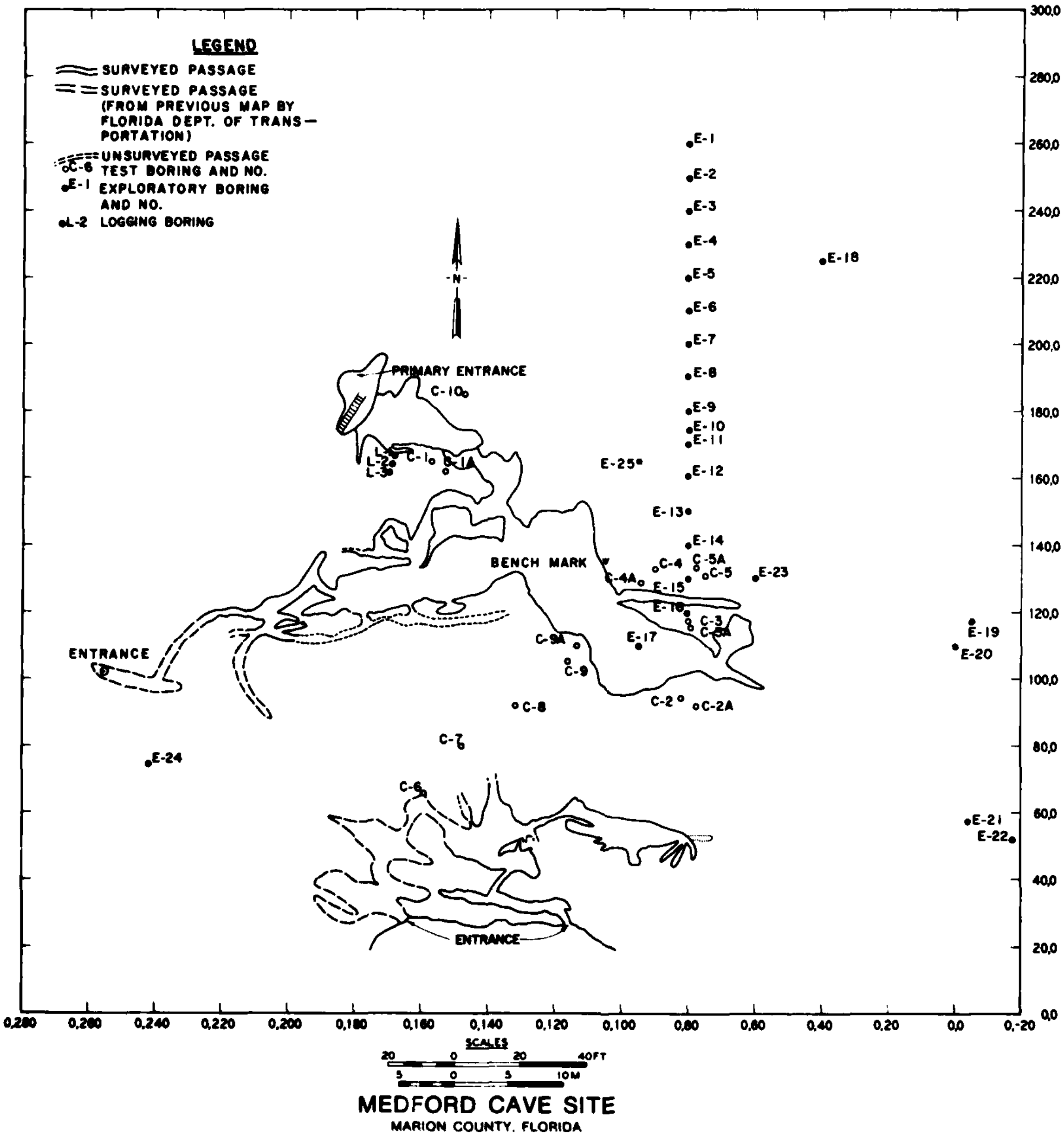


Figure 6. Map of site showing all boring locations

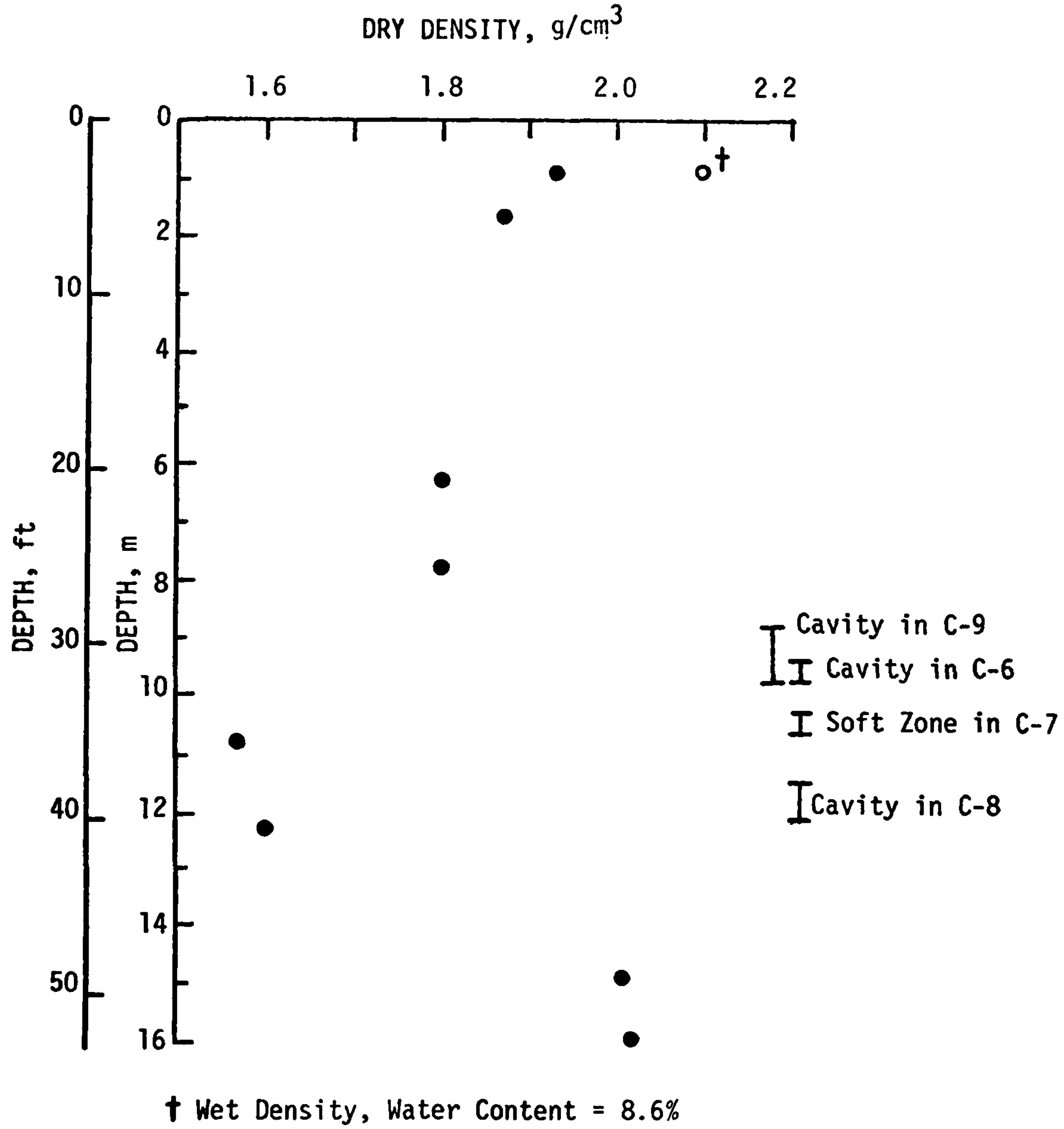


Figure 7. Limestone densities, Boring C-6

North →

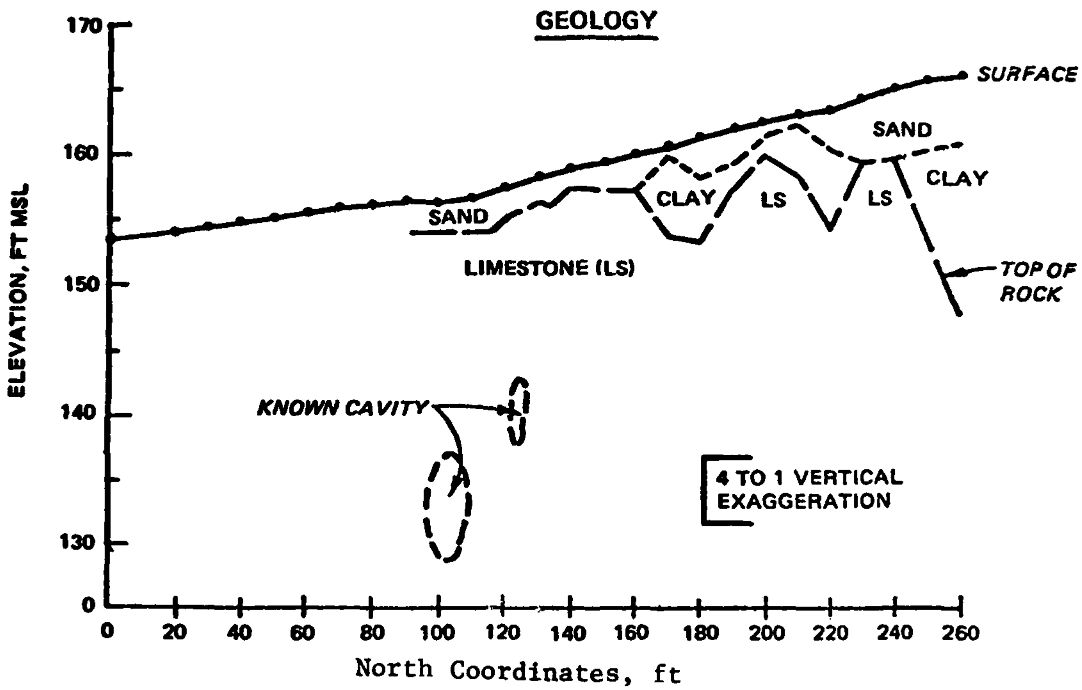


Figure 8. Geologic profile along 80W line

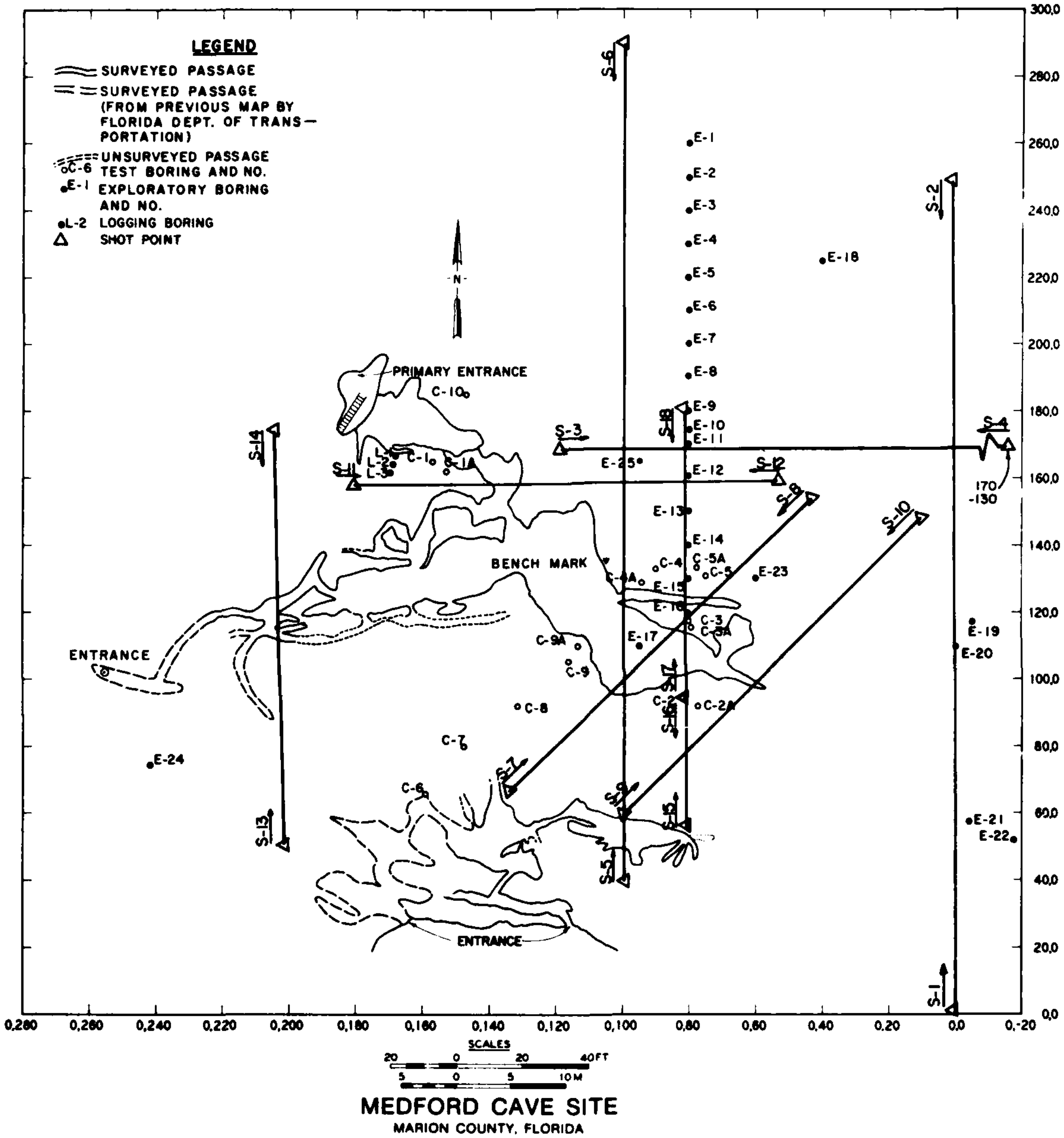


Figure 9. Surface refraction seismic test layout

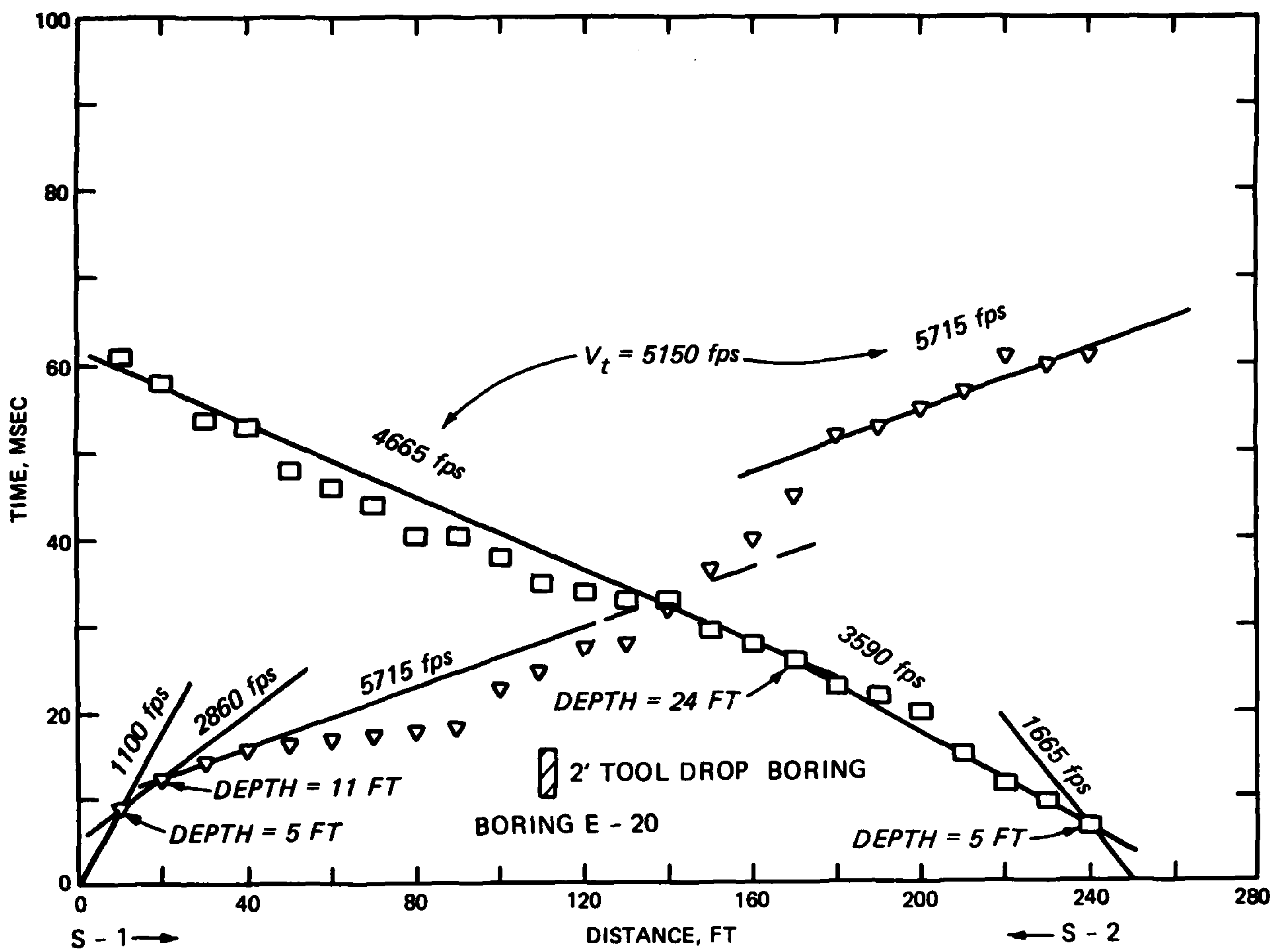


Figure 10. P-wave arrival time versus distance, traverses S-1 and S-2

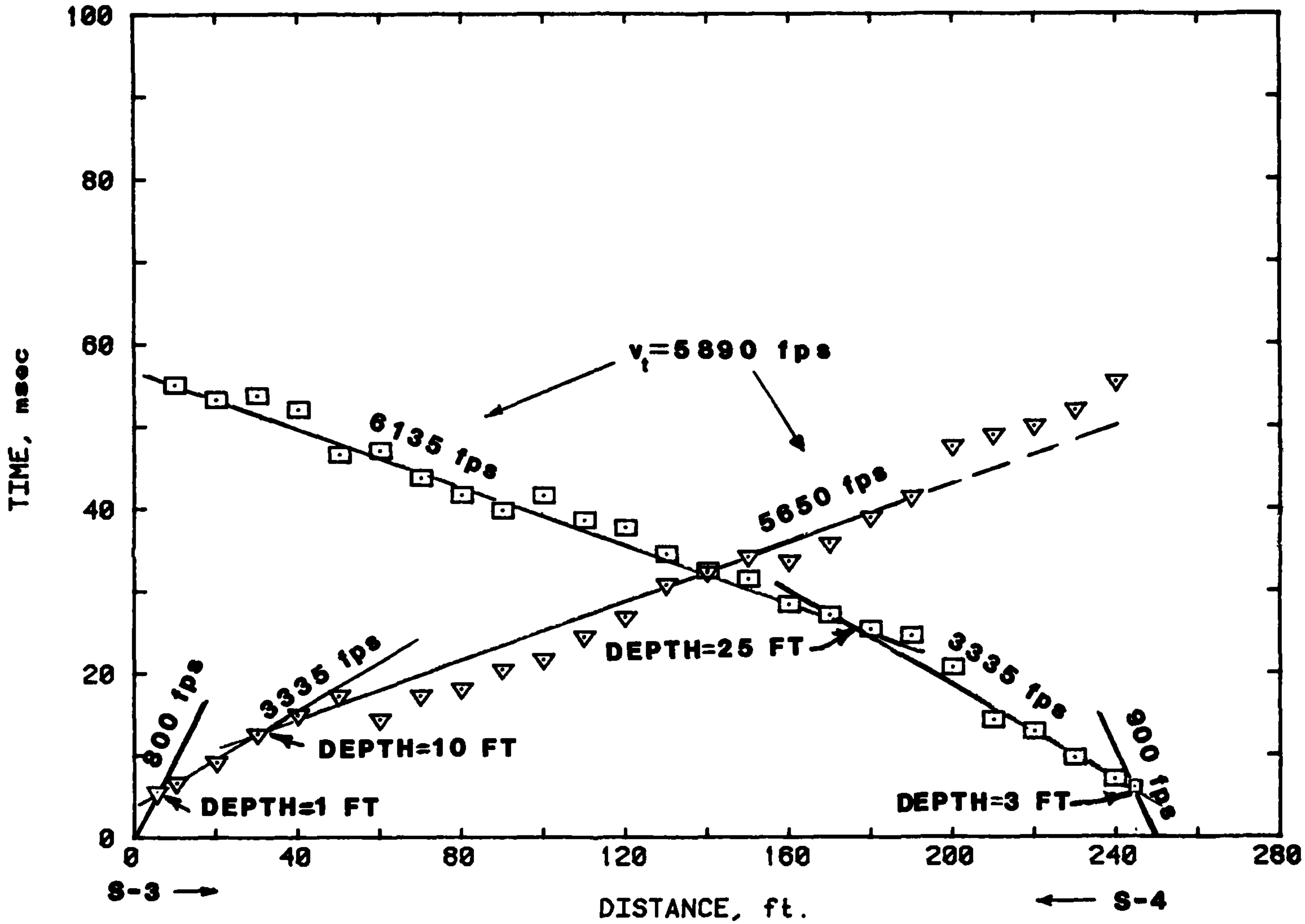


Figure 11. P-wave arrival time versus distance, traverses S-3 and S-4

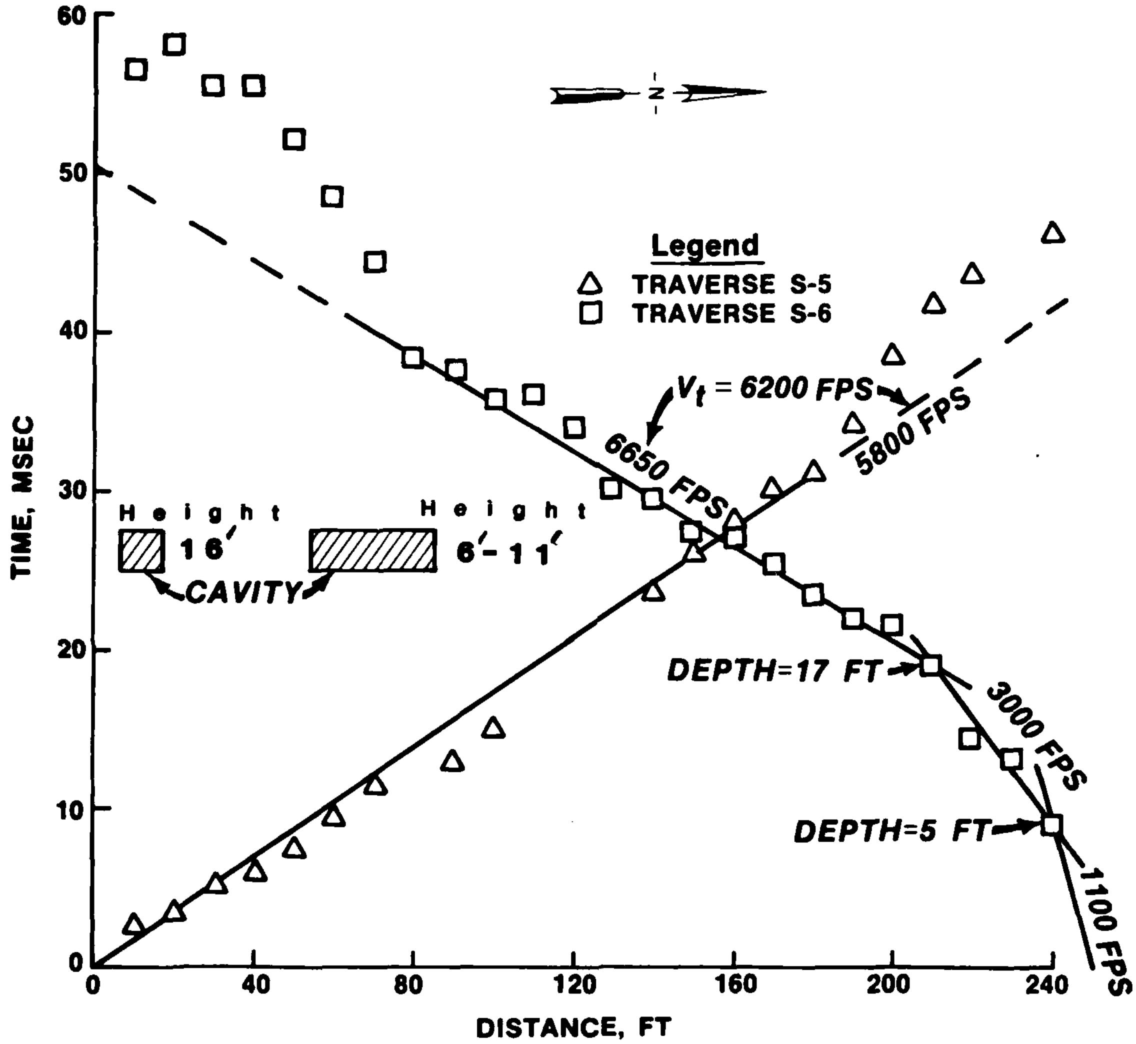


Figure 12. P-wave arrival time versus distance, traverses S-5 and S-6

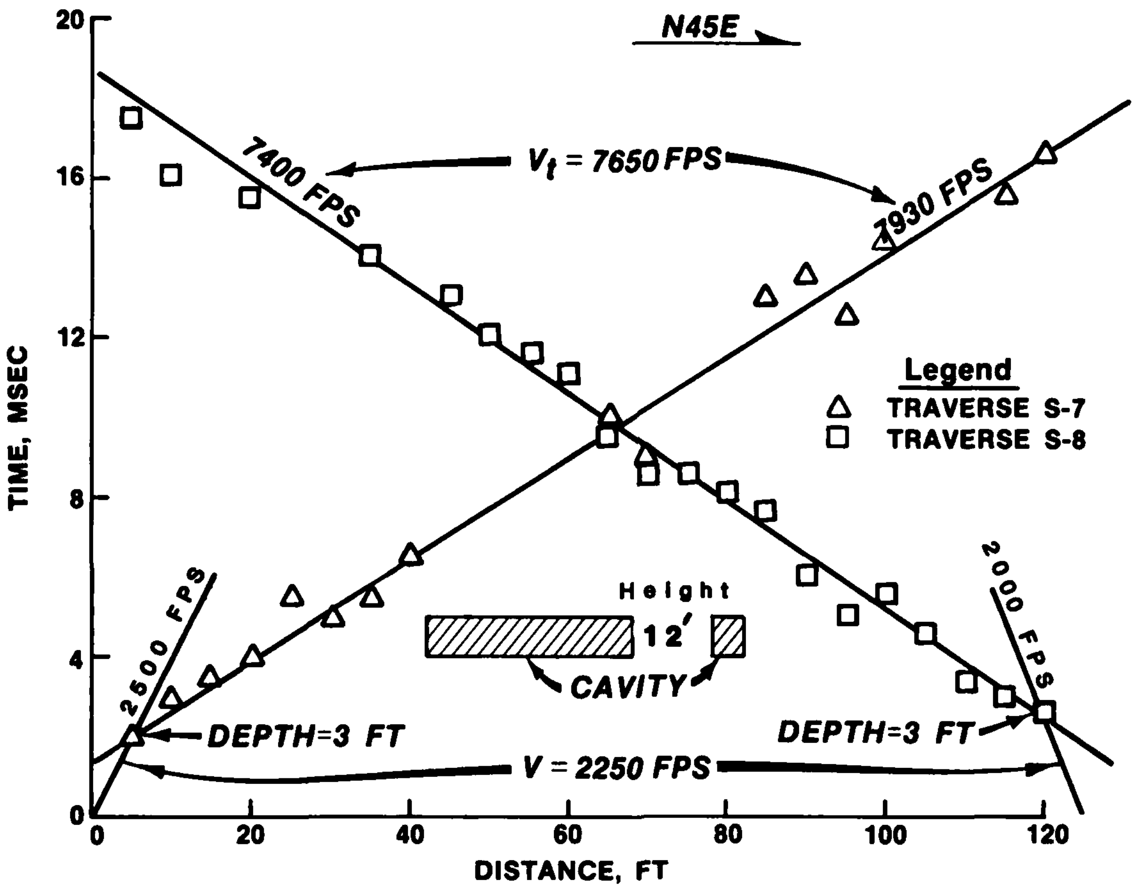


Figure 13. P-wave arrival time versus distance, traverses S-7 and S-8

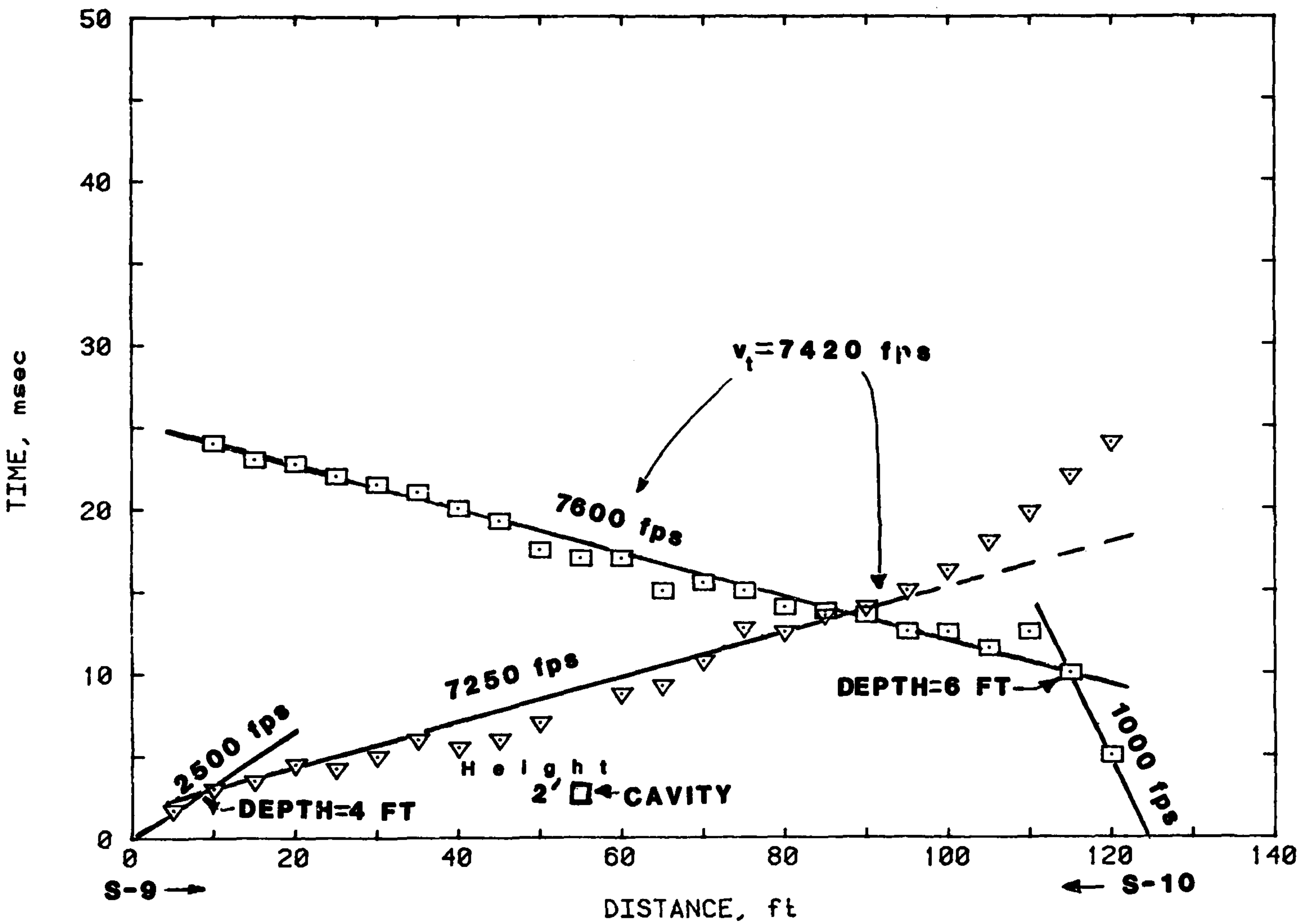


Figure 14. P-wave arrival time versus distance, traverses S-9 and S-10

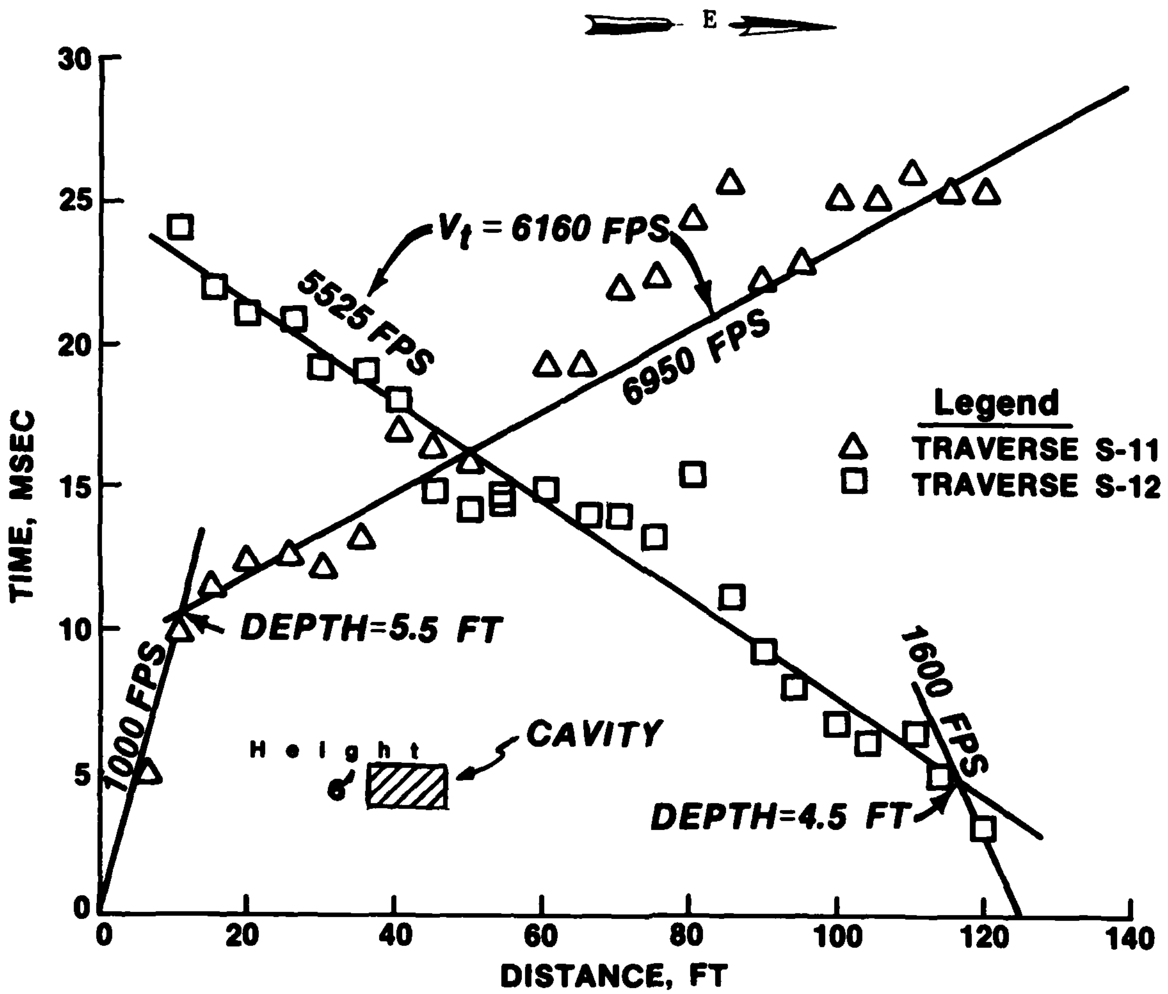


Figure 15. P-wave arrival time versus distance, traverses S-11 and S-12

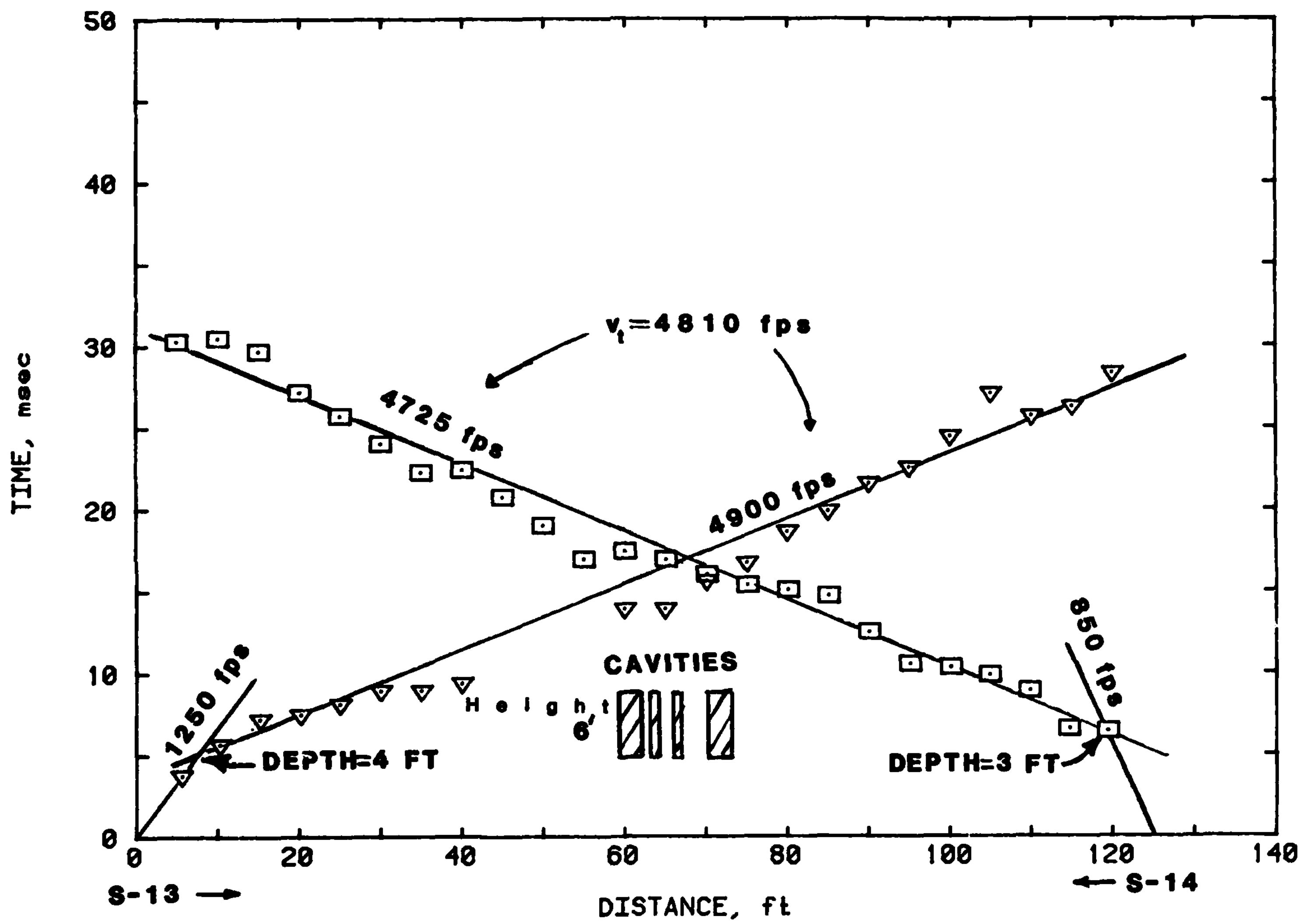


Figure 16. P-wave arrival time versus distance, traverses S-13 and S-14

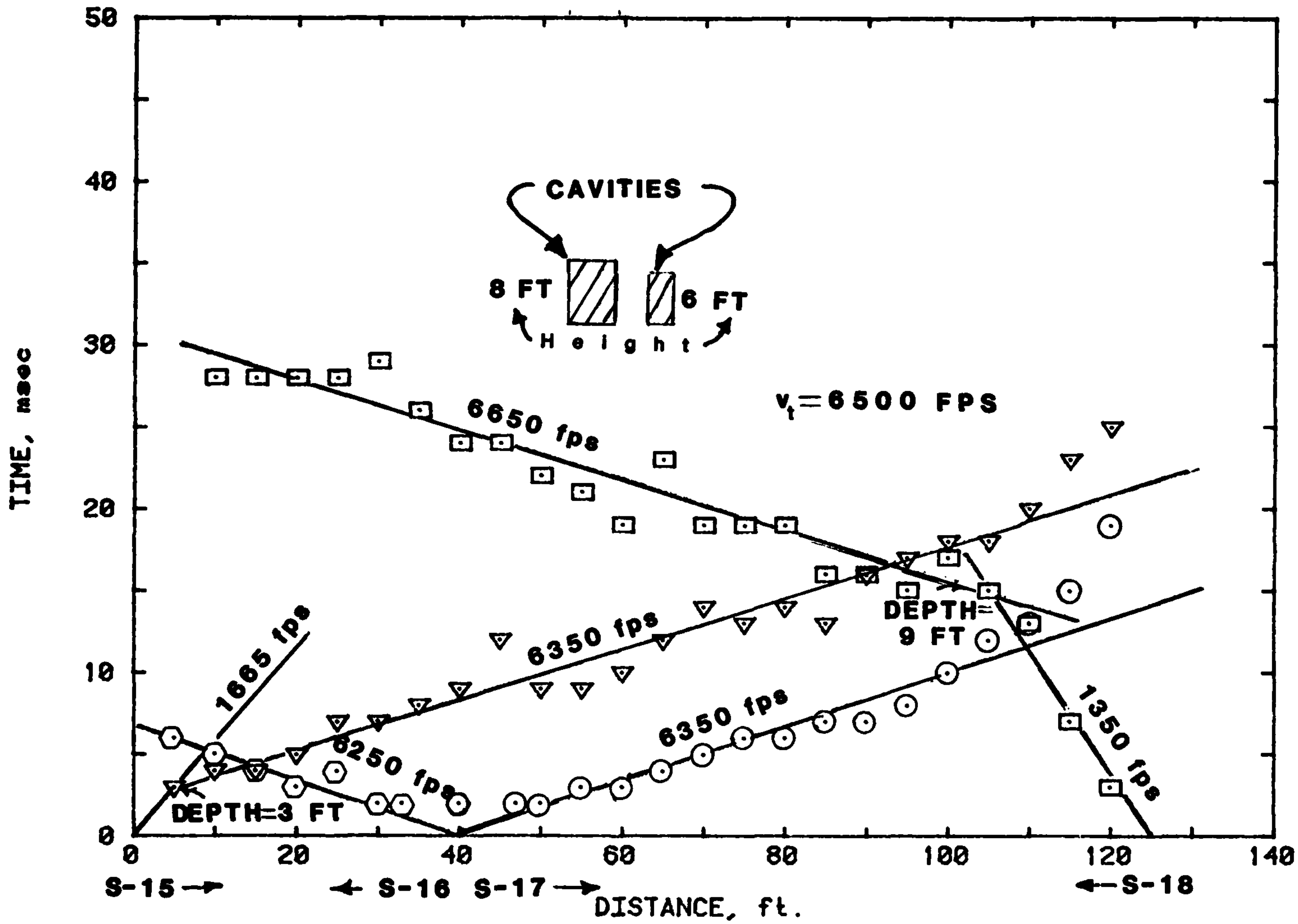


Figure 17. P-wave arrival time versus distance, traverses S-15, S-16, S-17, and S-18

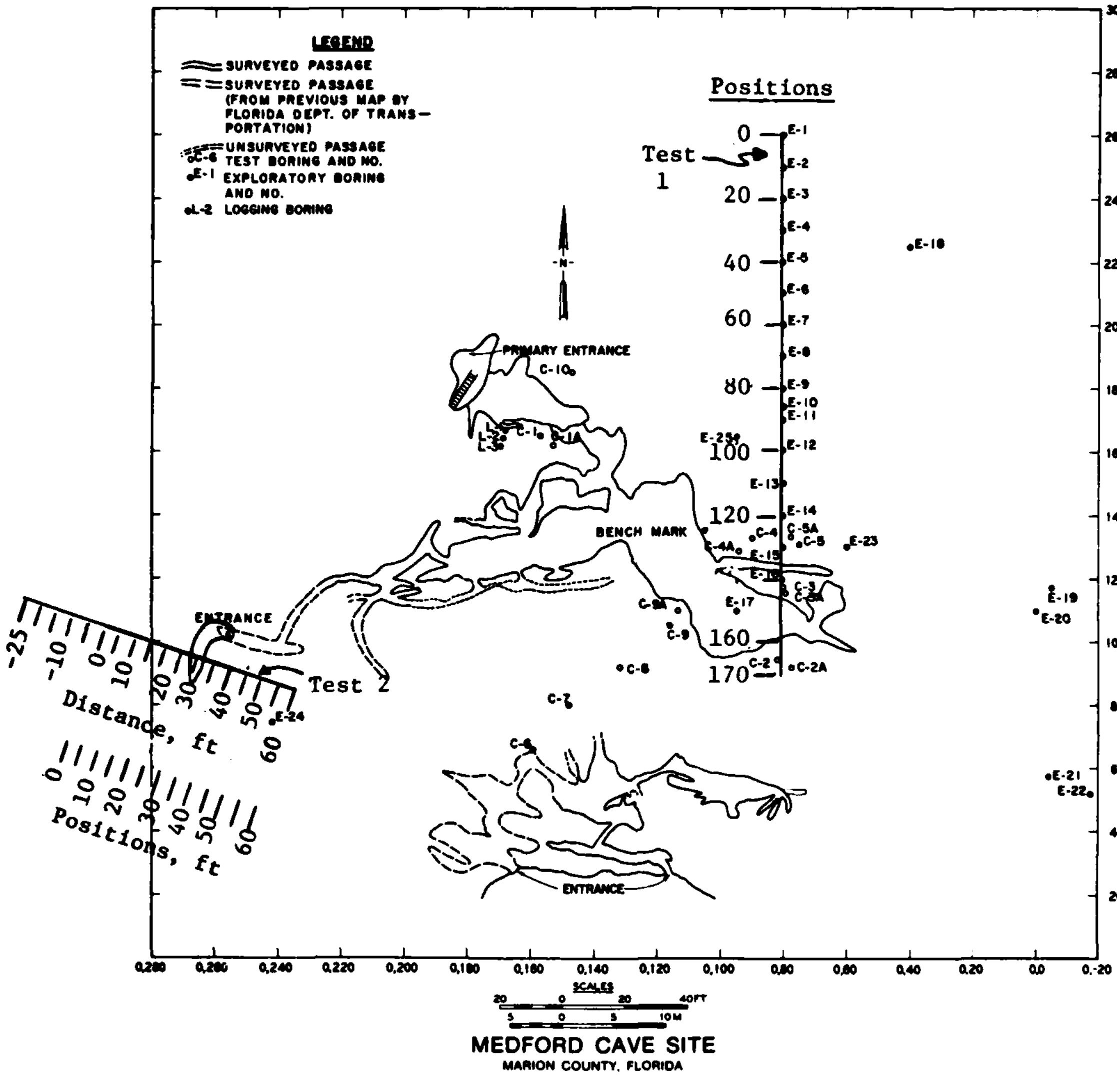


Figure 18. Seismic constant-spacing test layout for tests 1 and 2

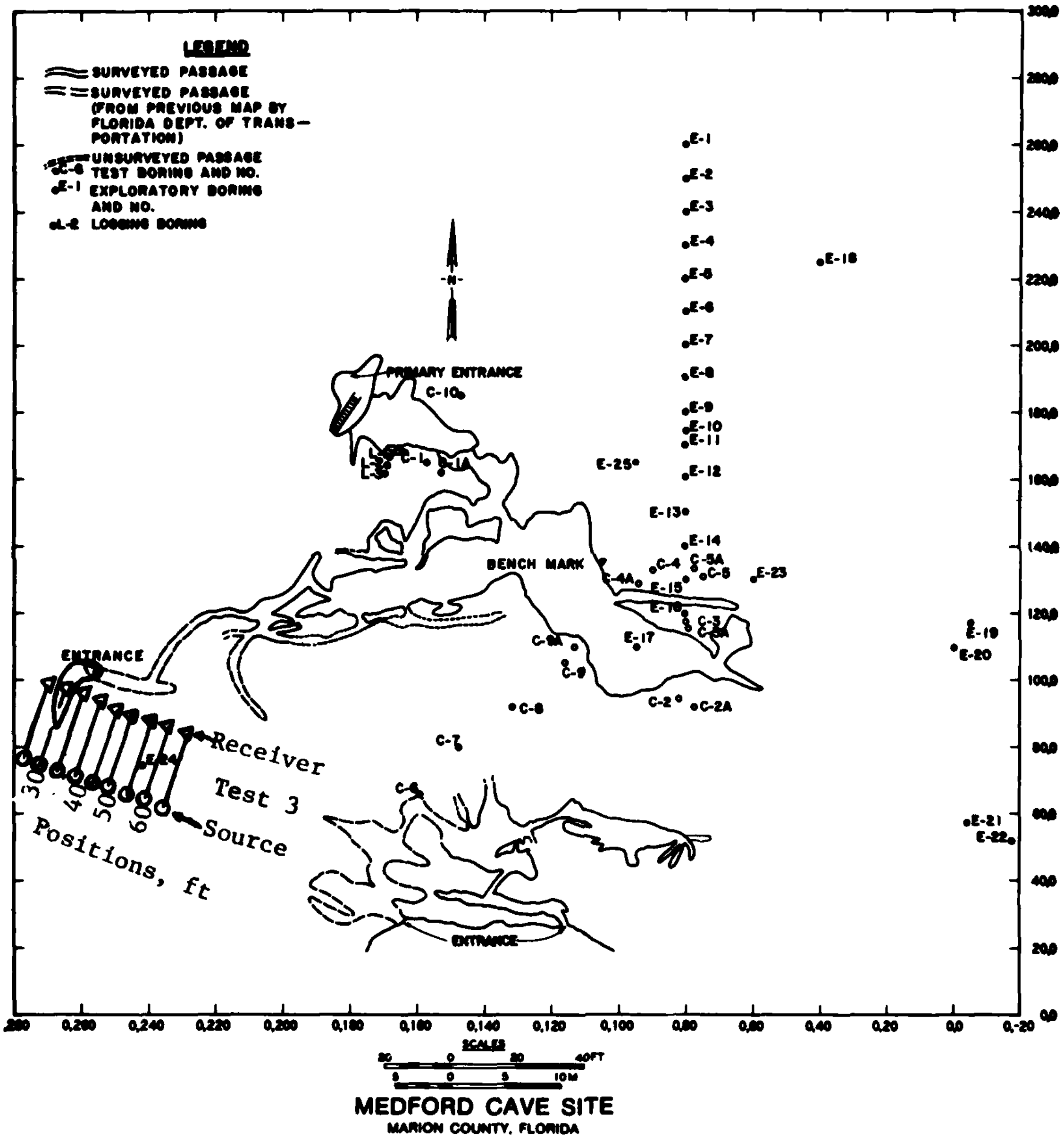


Figure 19. Seismic constant-spacing test layout for test 3

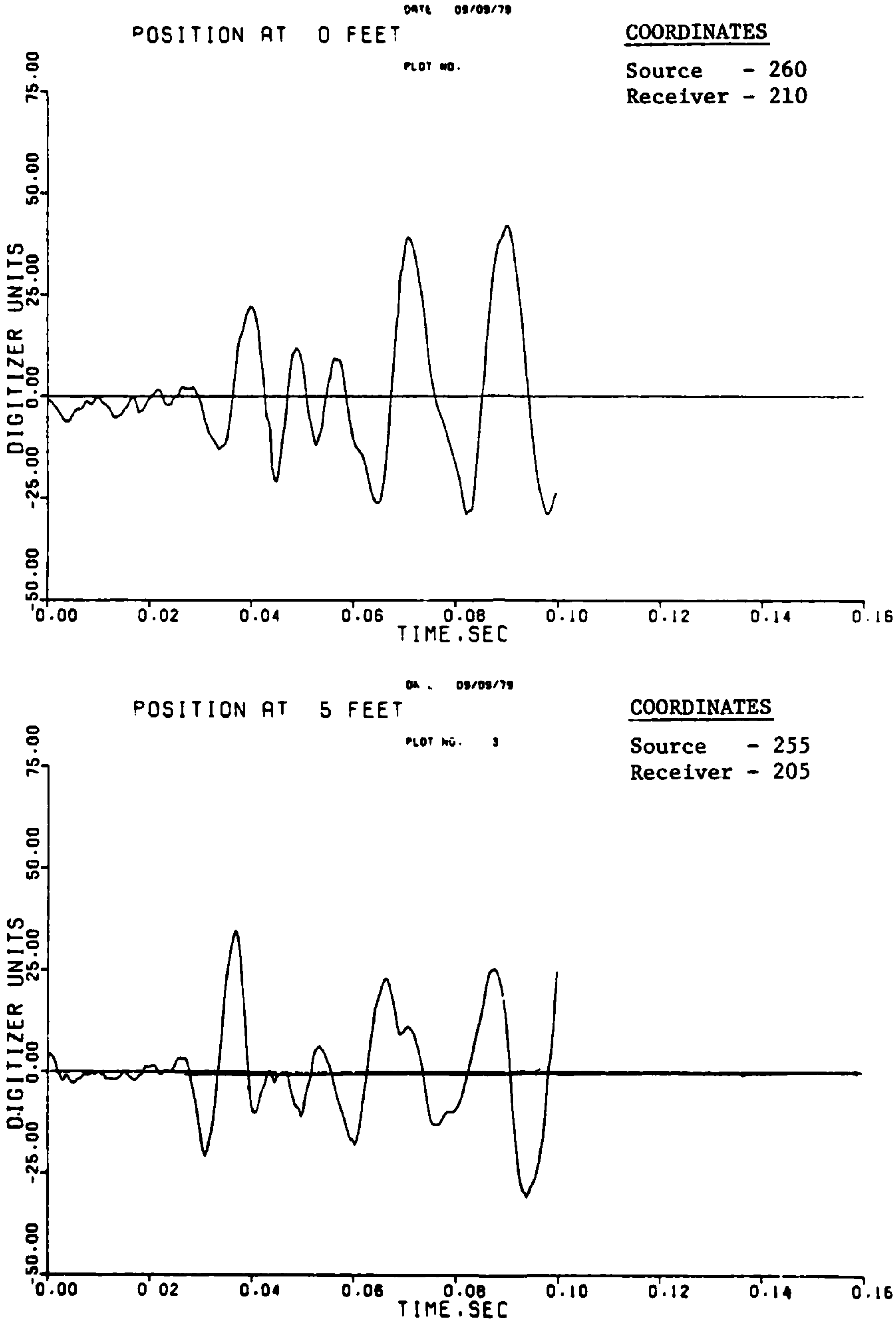


Figure 20. Digitized oscillograms for constant-spacing tests along 80W line, positions 0 and 5 ft

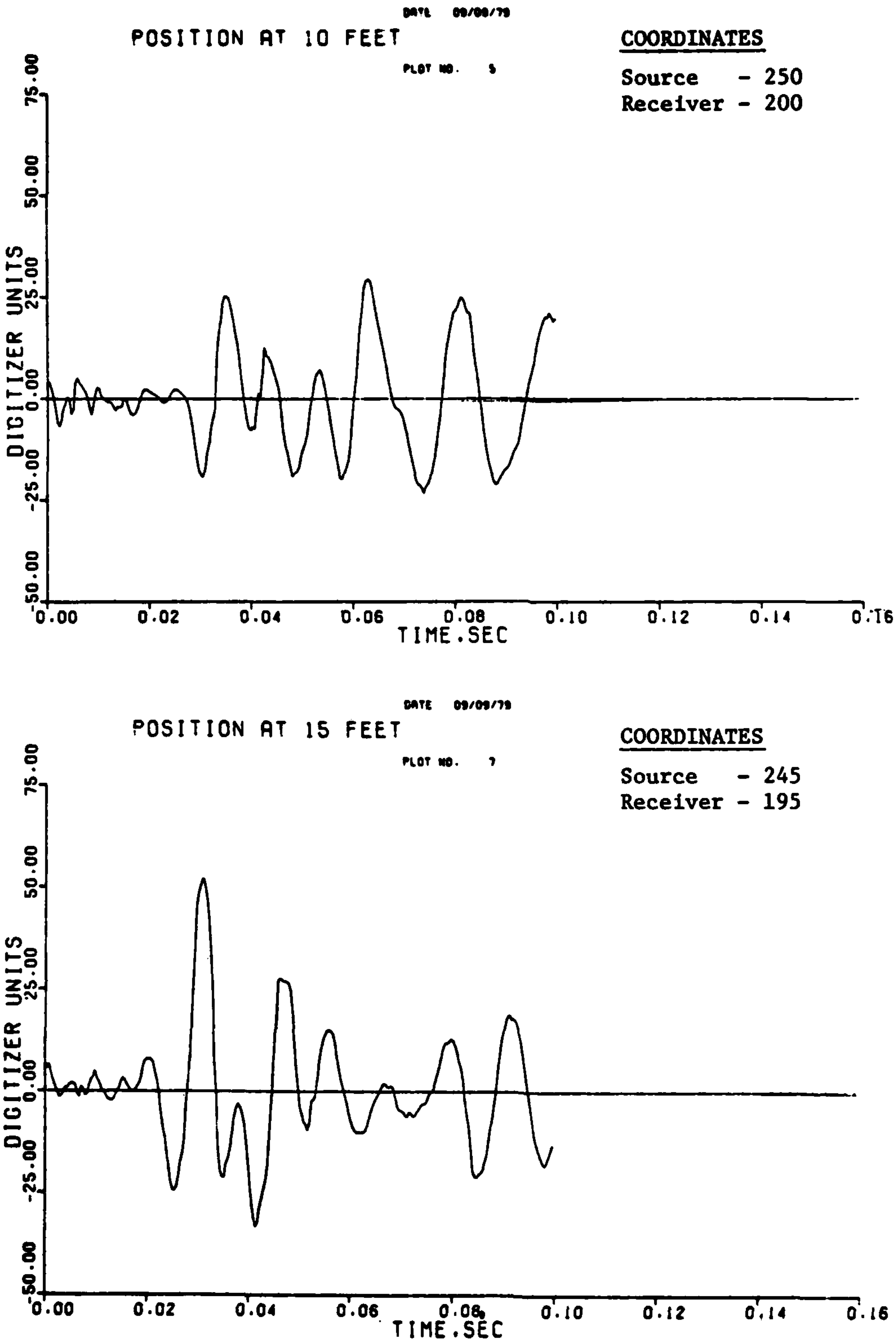
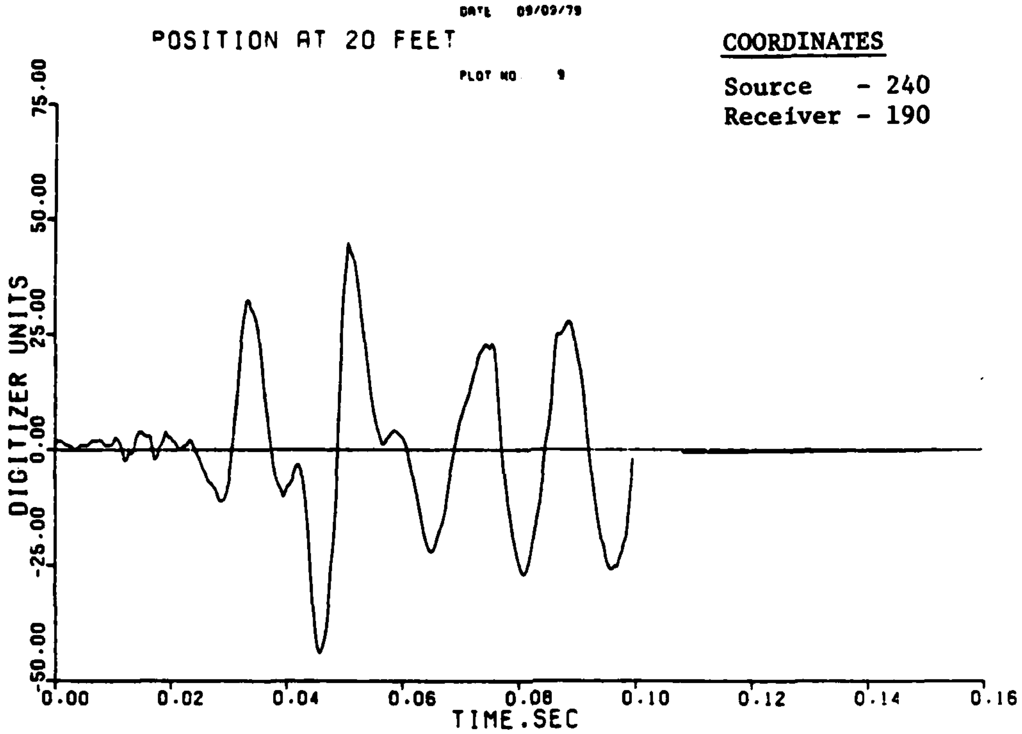


Figure 21. Digitized oscillograms for constant-spacing tests along 80W line, positions 10 and 15 ft



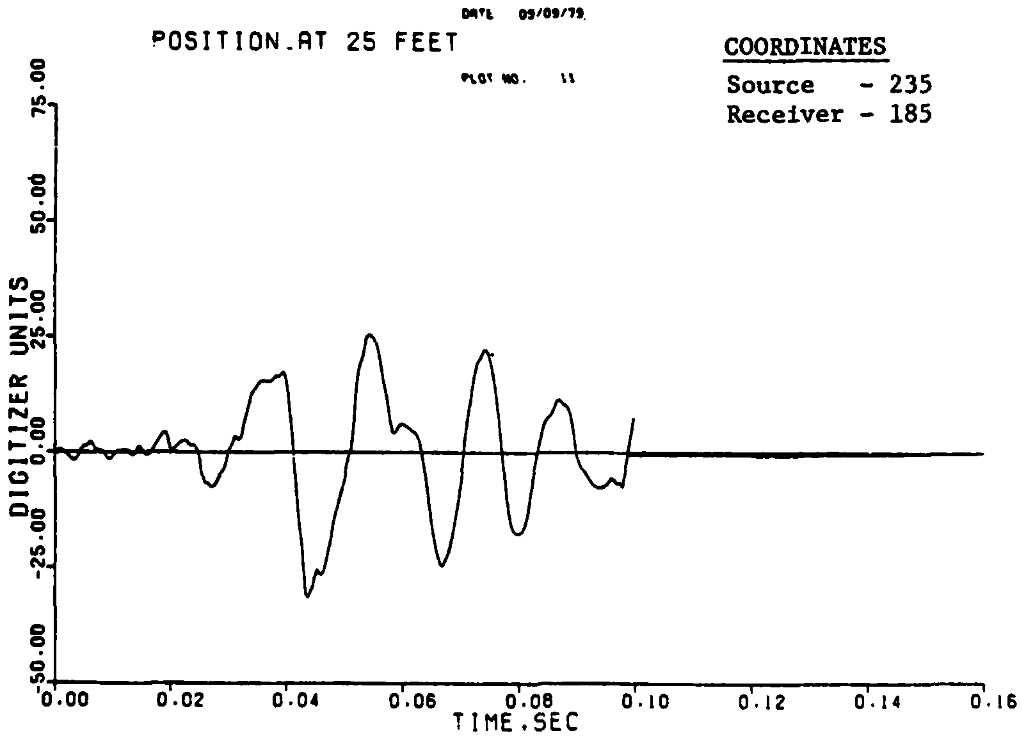
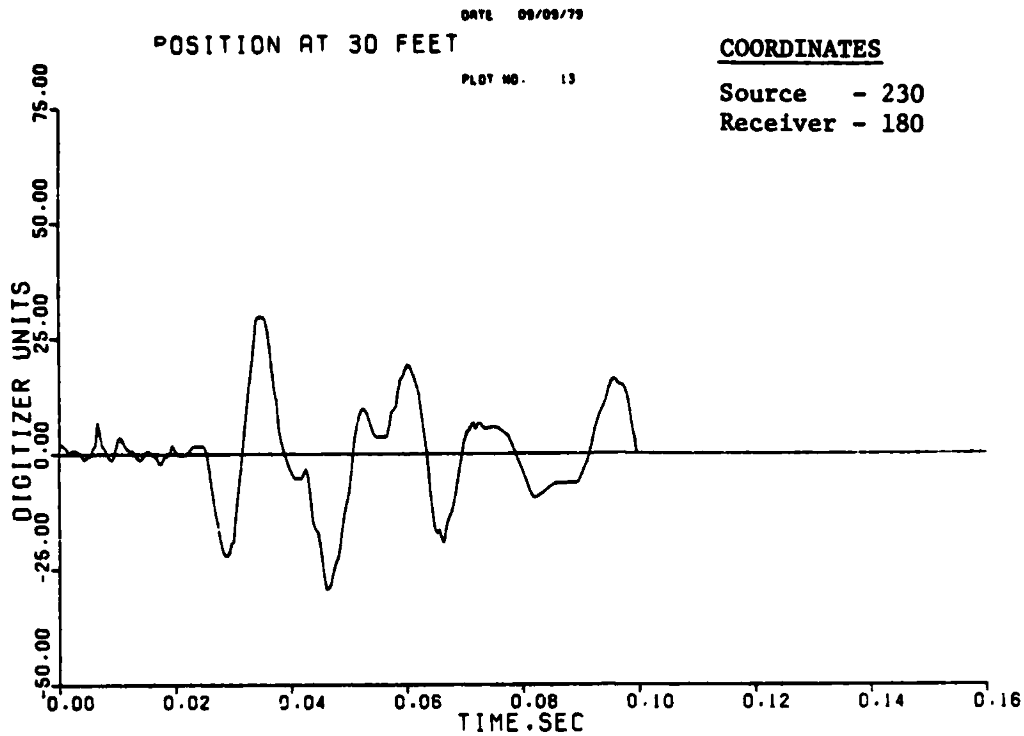


Figure 22. Digitized oscillograms for constant-spacing tests along 80W line, positions 20 and 25 ft



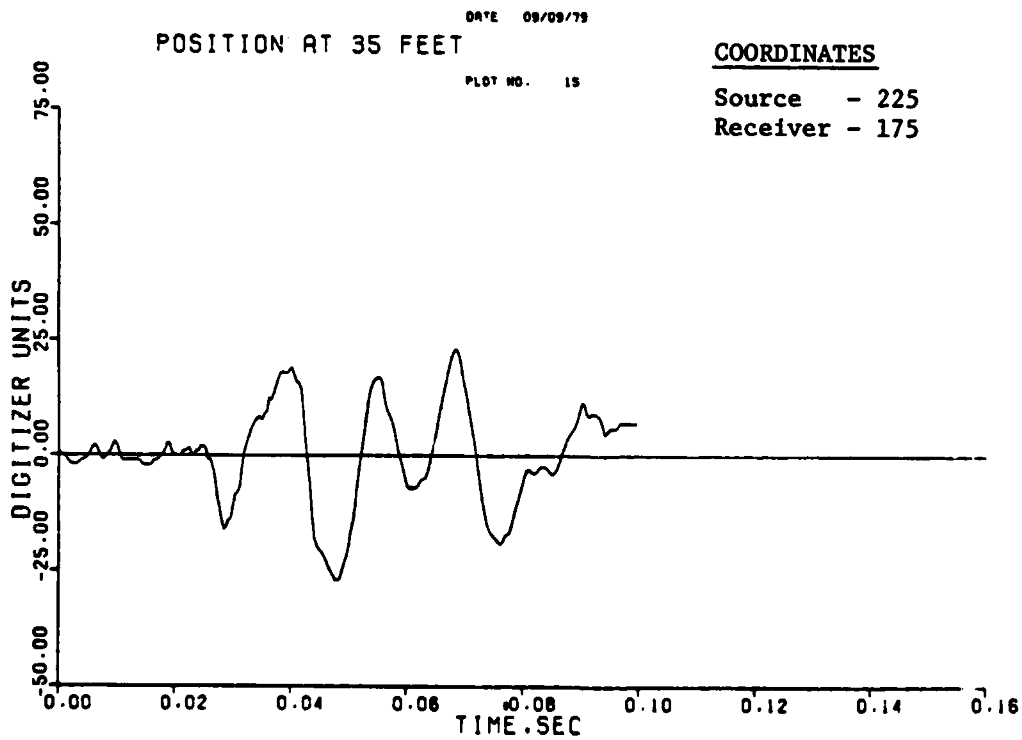
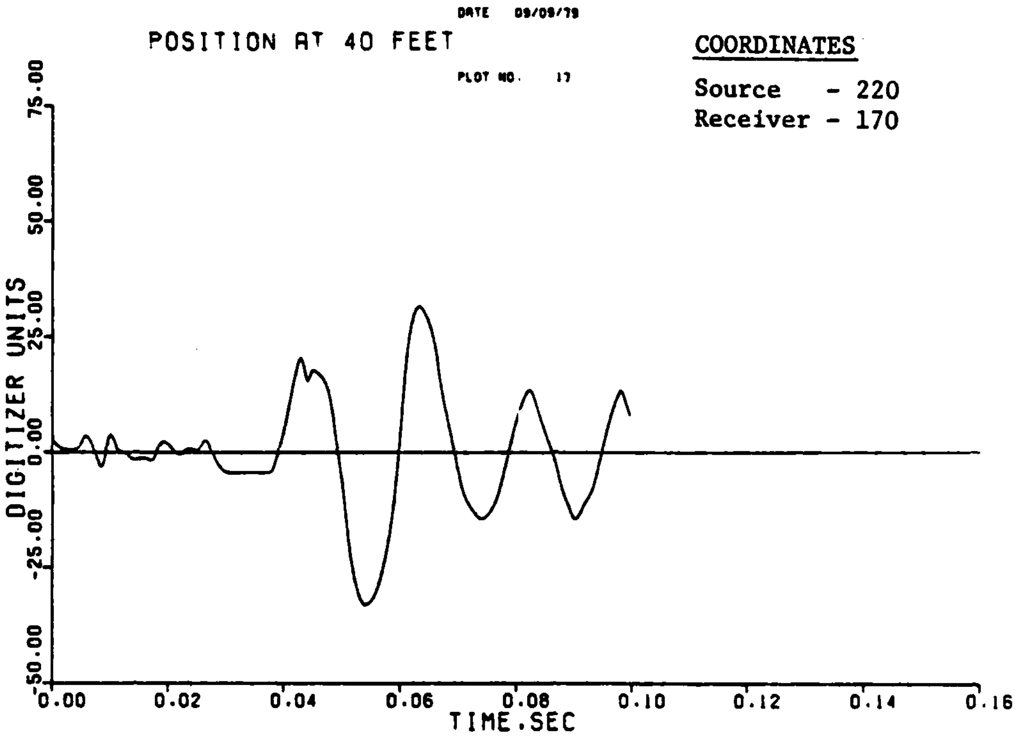


Figure 23. Digitized oscillograms for constant-spacing tests along 80W line, positions 30 and 35 ft



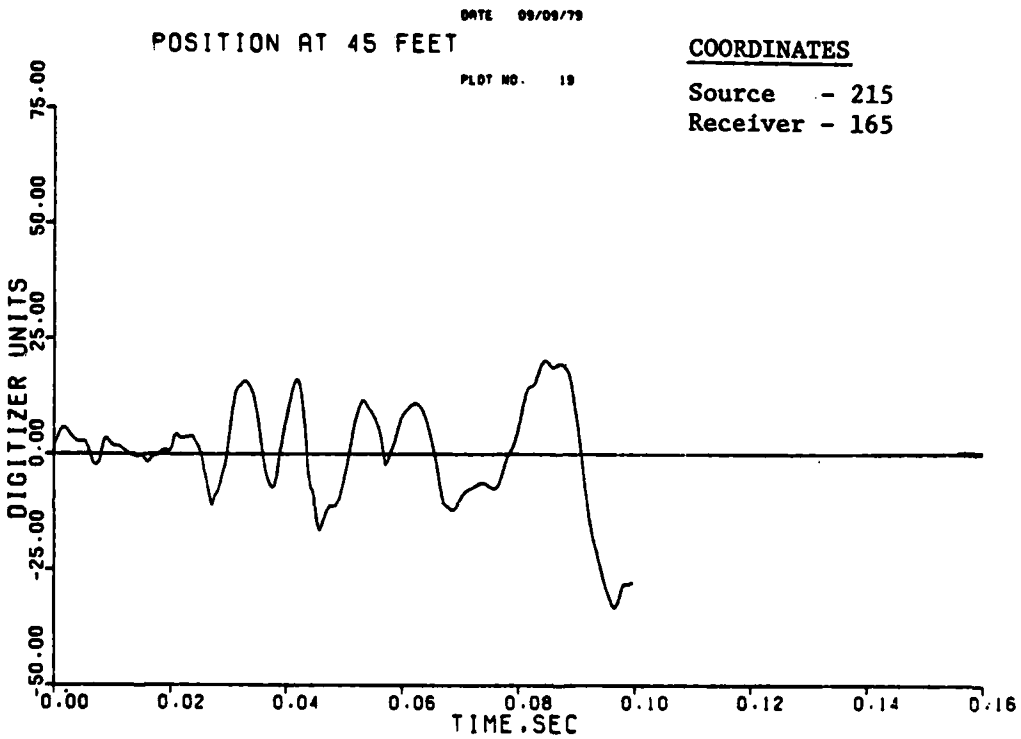
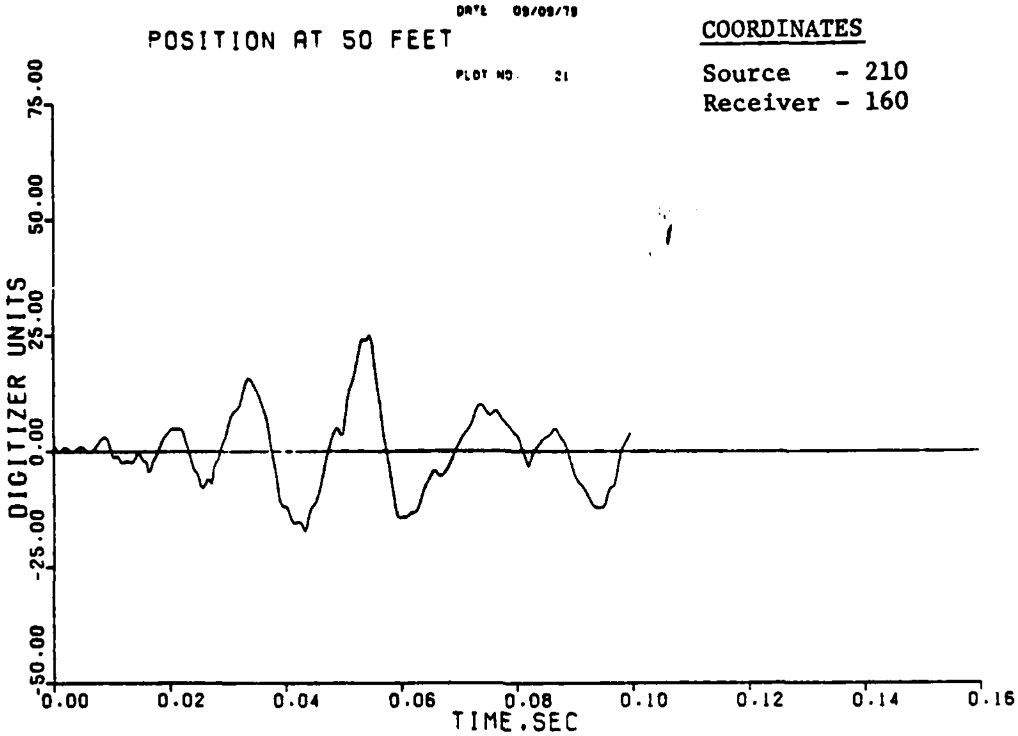


Figure 24. Digitized oscillograms for constant-spacing tests along 80W line, positions 40 and 45 ft



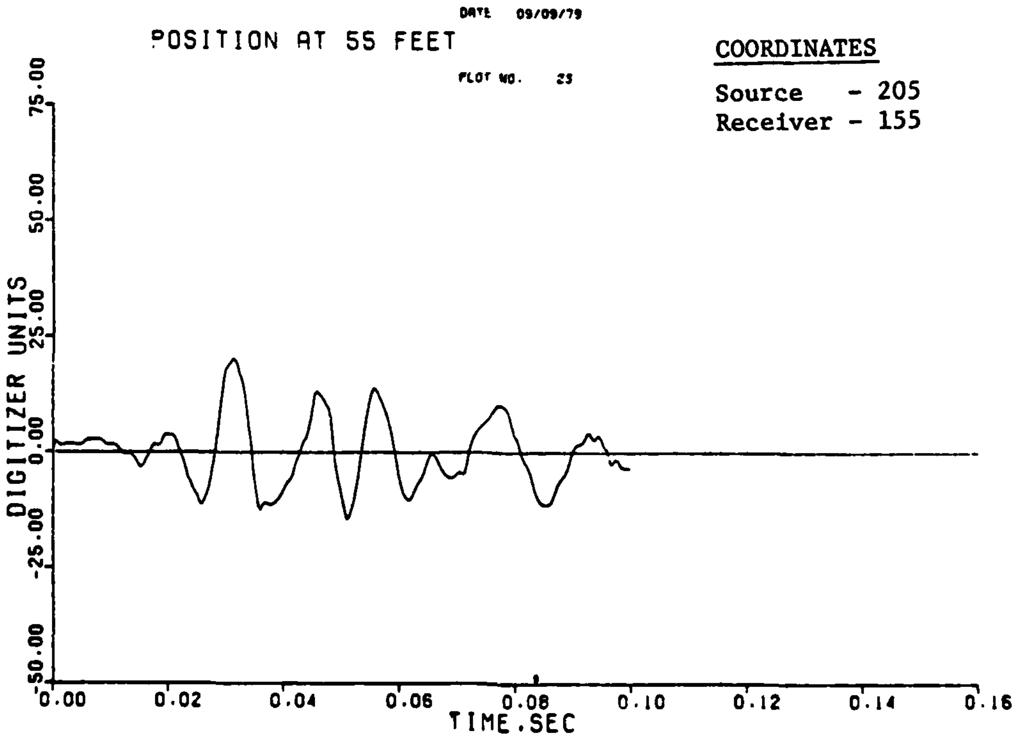
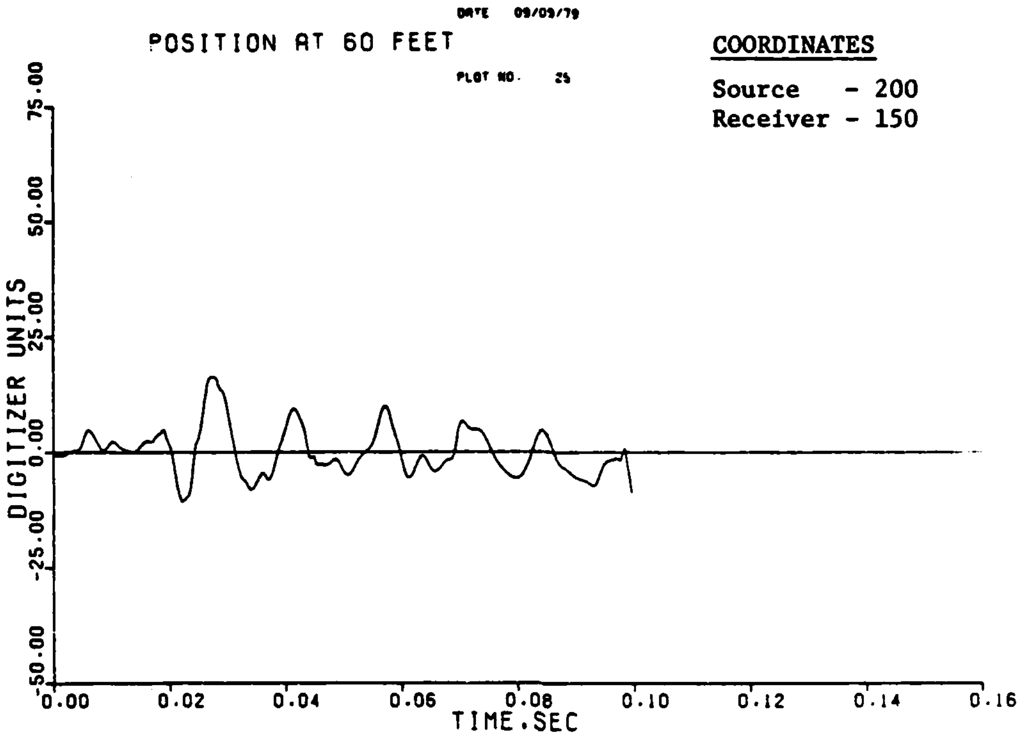


Figure 25. Digitized oscillograms for constant-spacing tests along 80W line, positions 50 and 55 ft



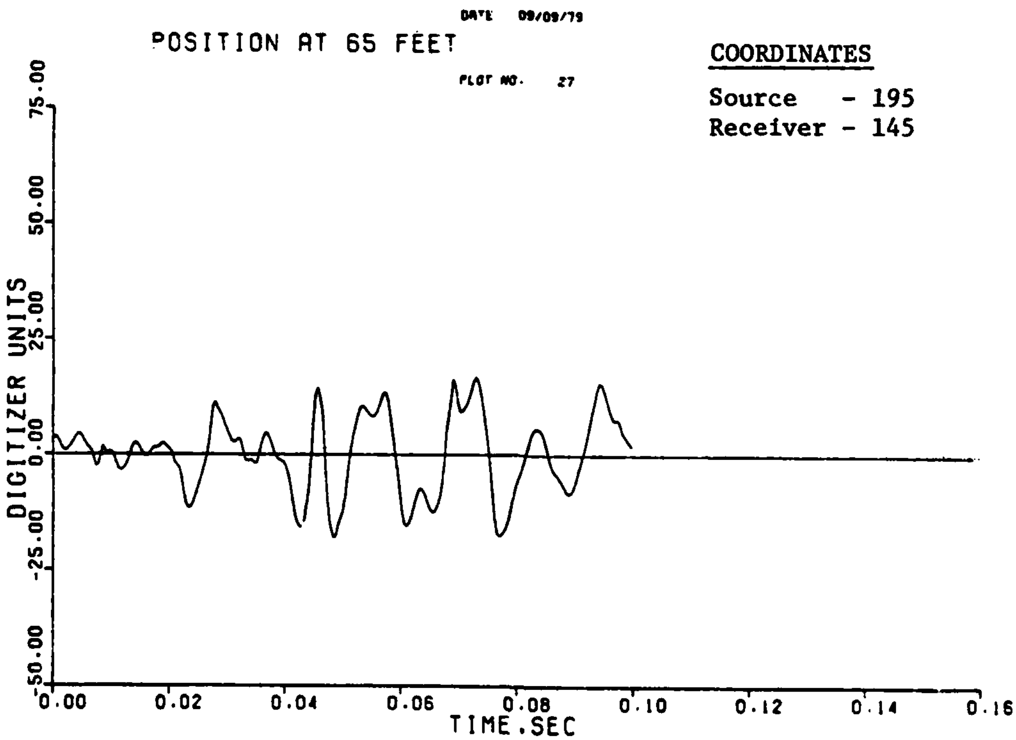


Figure 26. Digitized oscillograms for constant-spacing tests along 80W line, positions 60 and 65 ft

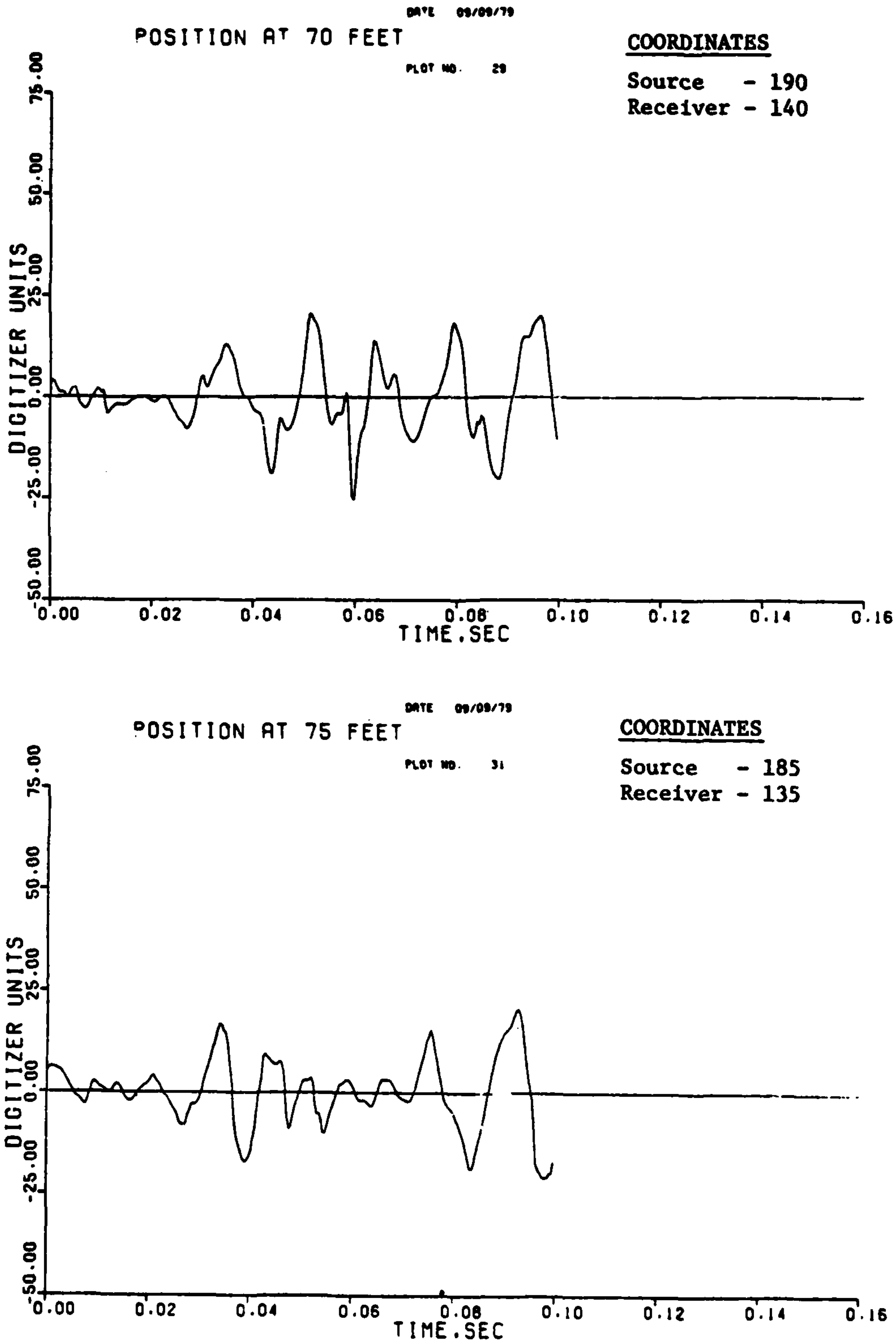


Figure 27. Digitized oscillograms for constant-spacing tests along 80W line, positions at 70 and 75 ft

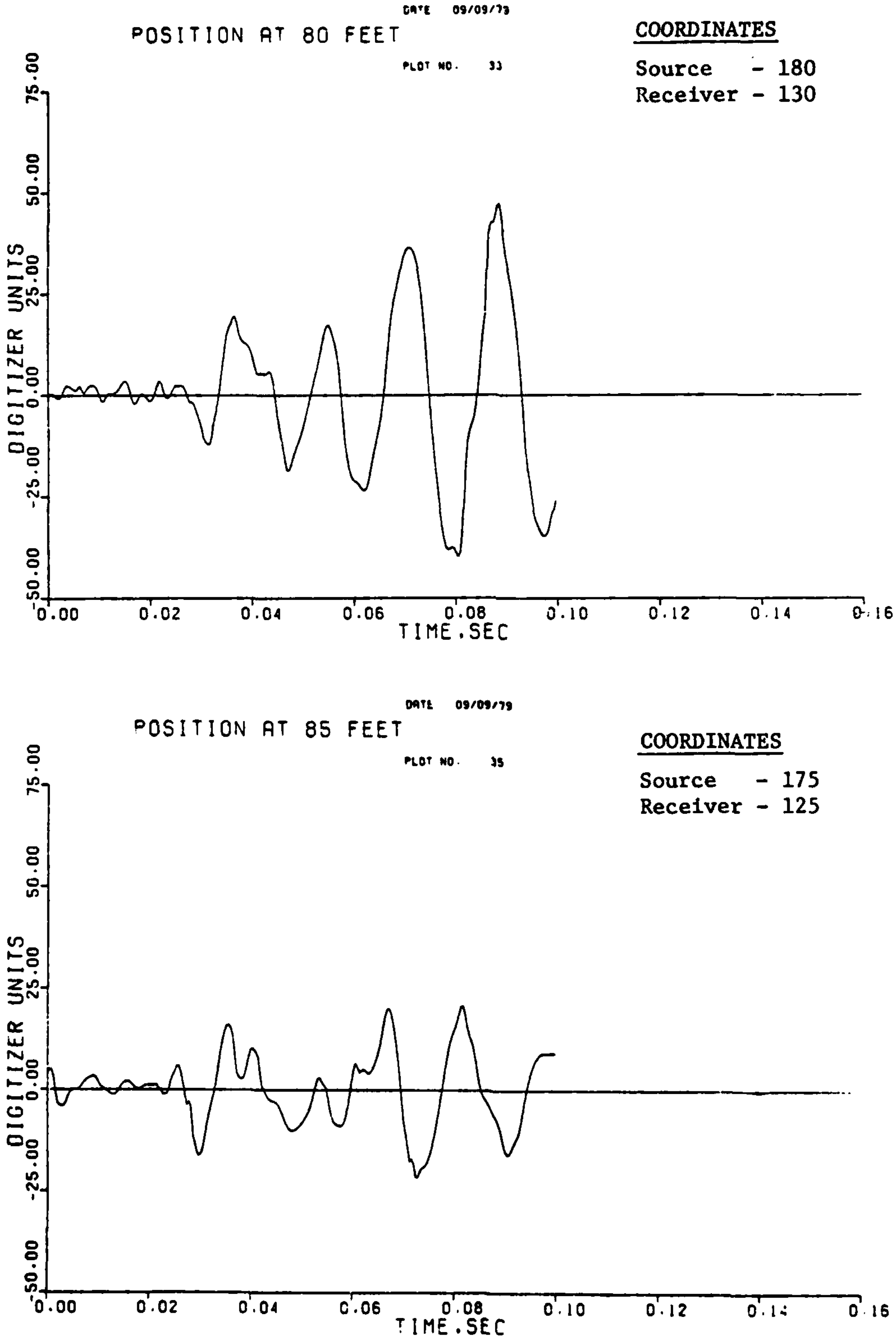
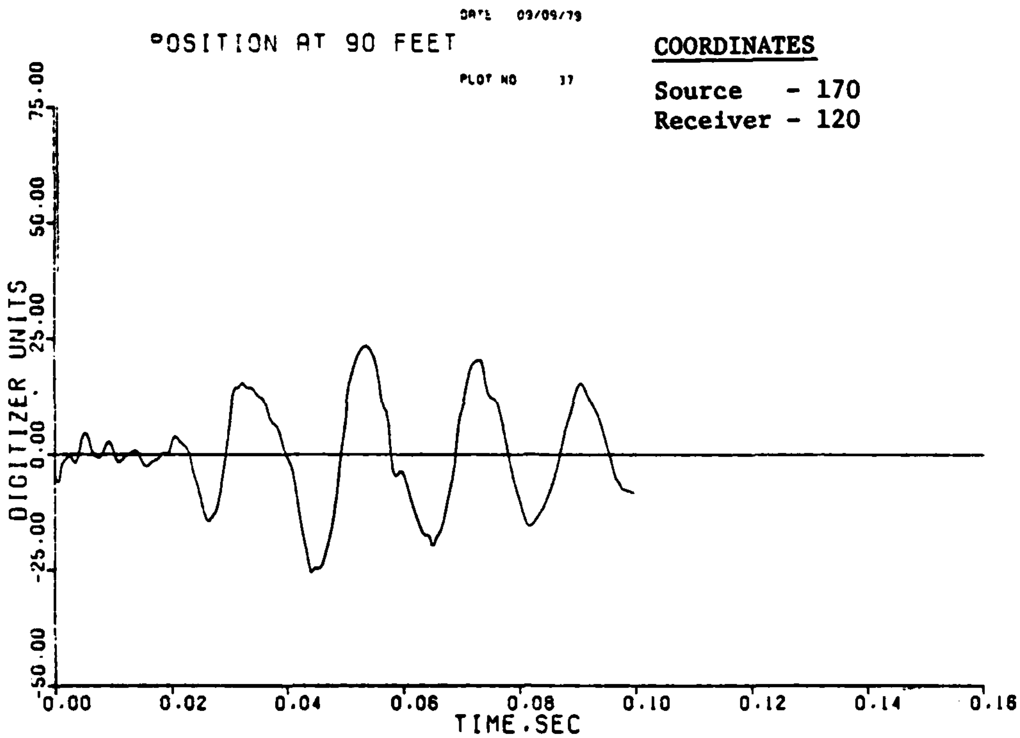


Figure 28. Digitized oscillograms for constant-spacing tests along 80W line, positions 80 and 85 ft



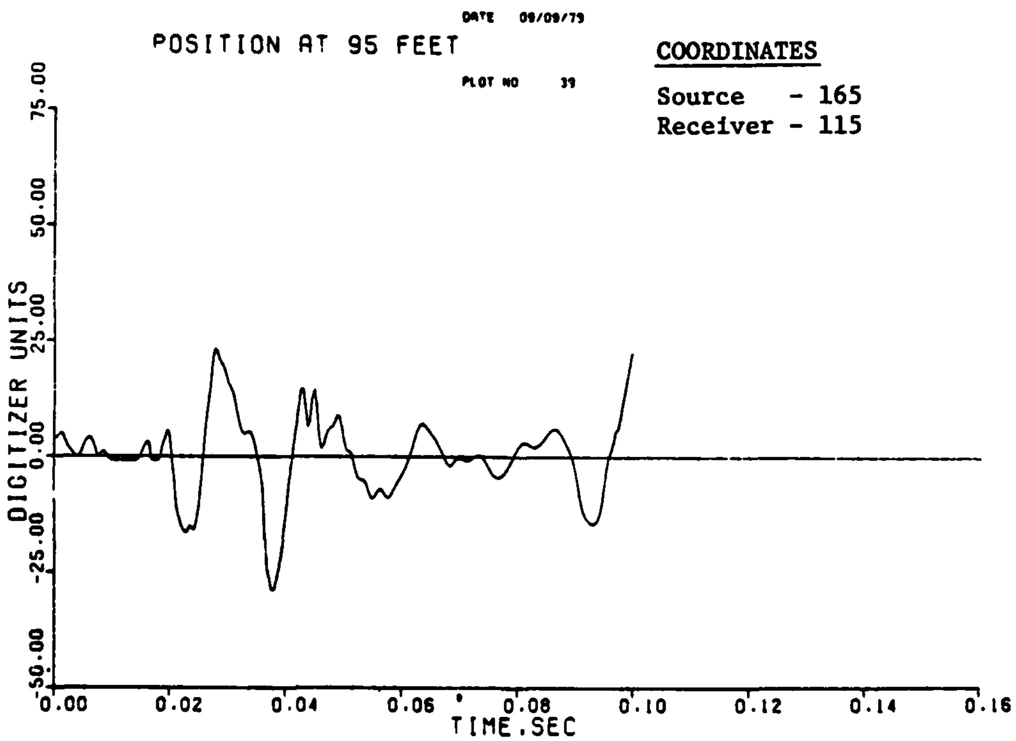
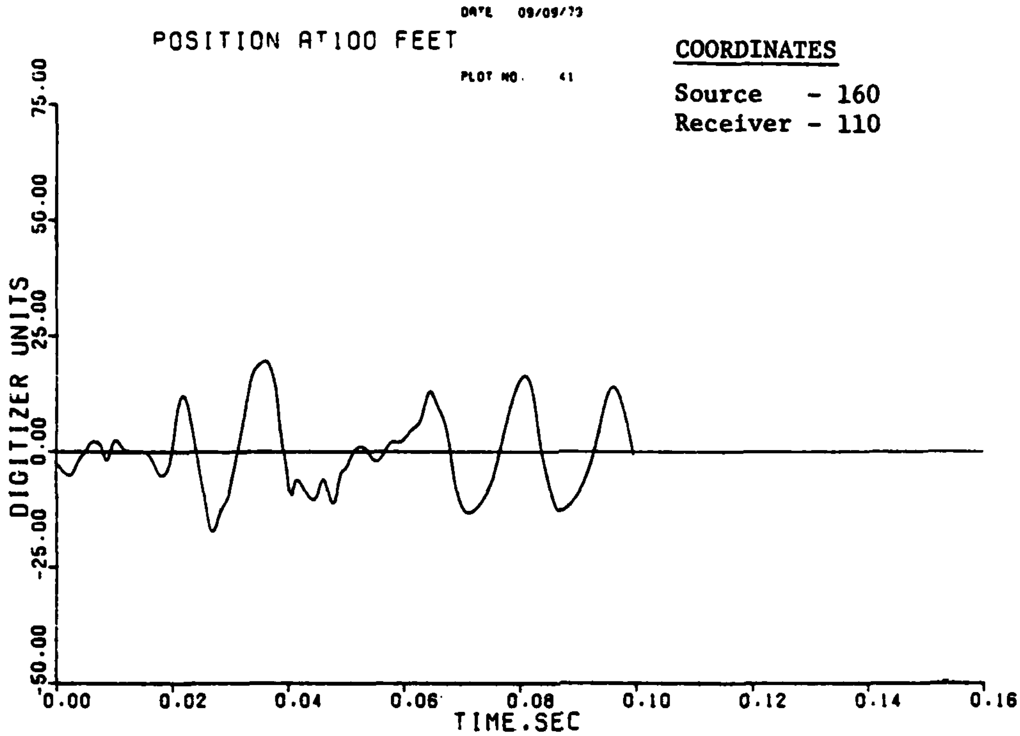


Figure 29. Digitized oscillograms for constant-spacing tests along 80W line, positions 90 and 95 ft



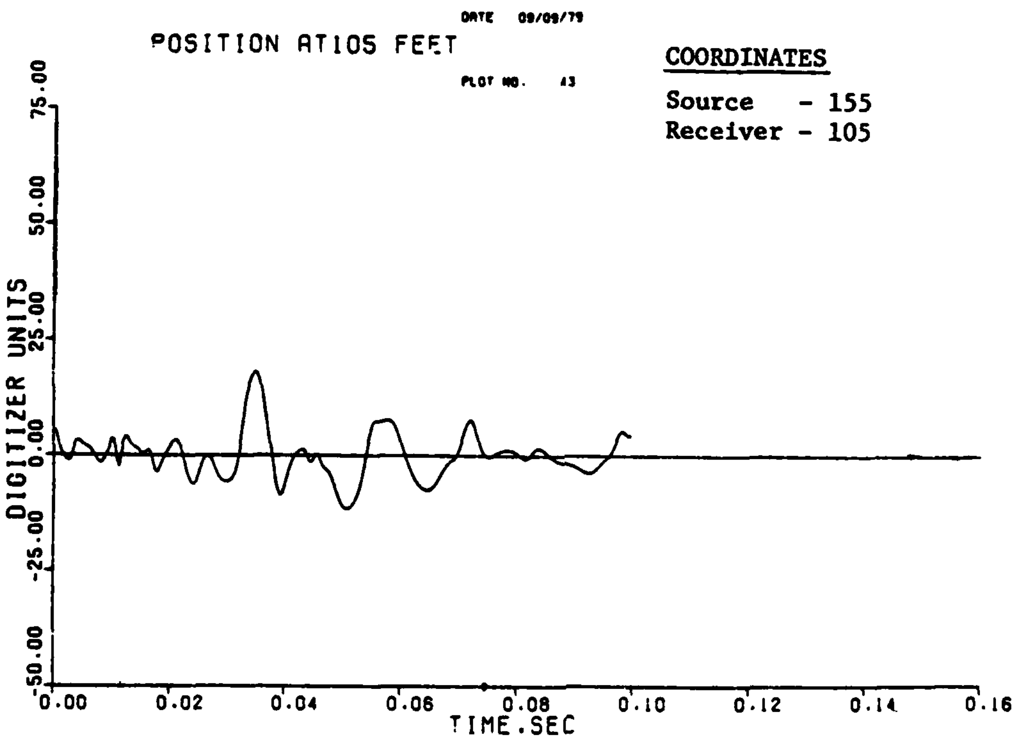
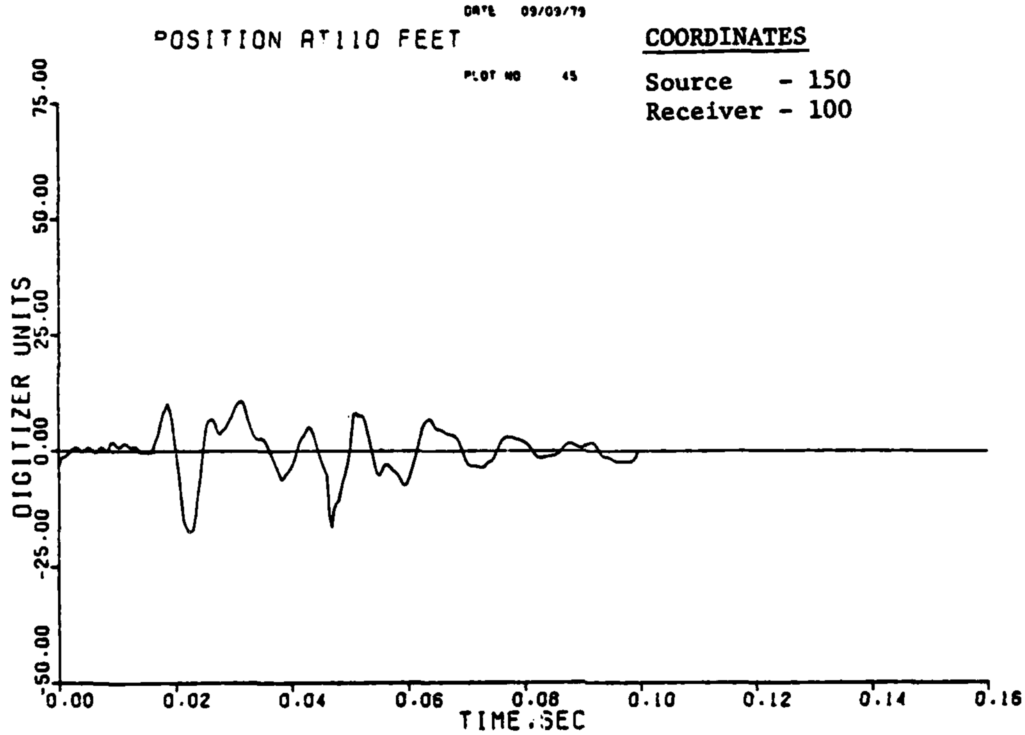


Figure 30. Digitized oscillograms for constant-spacing tests along 80W line, positions 100 and 105 ft



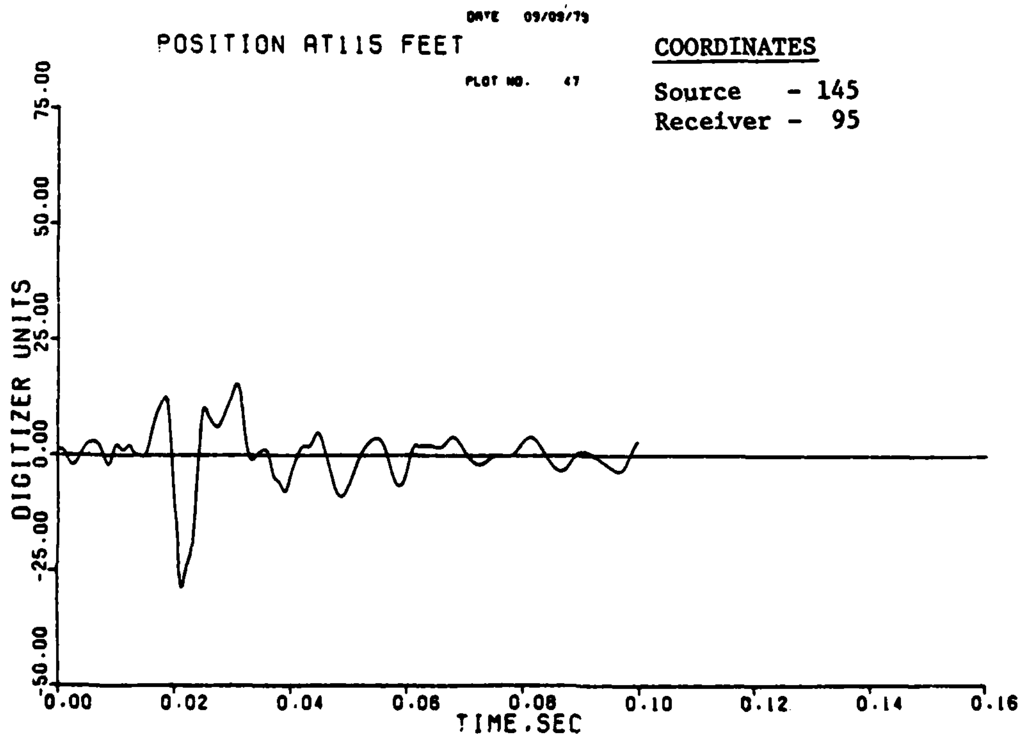
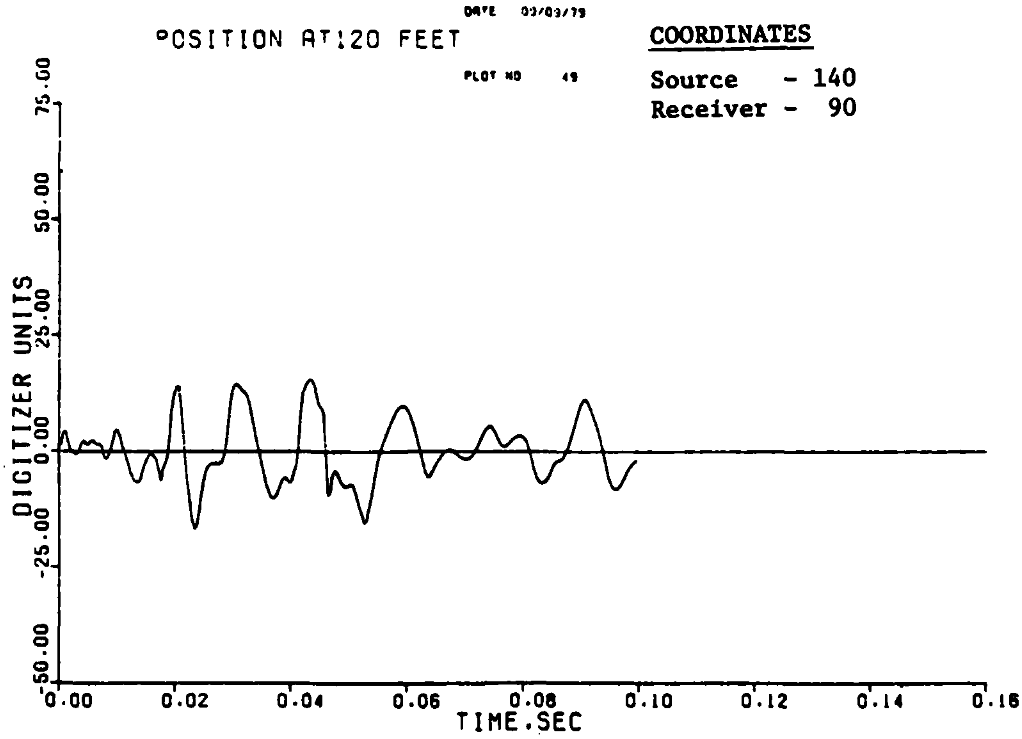


Figure 31. Digitized oscillograms for constant-spacing tests along 80W line, positions 110 and 115 ft



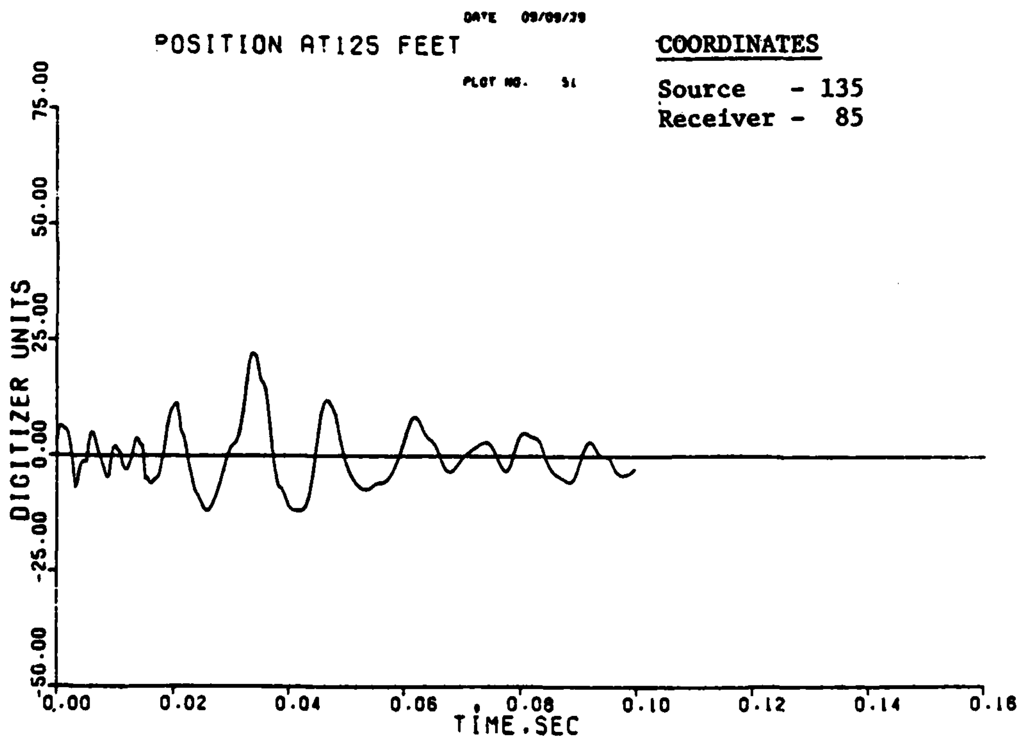
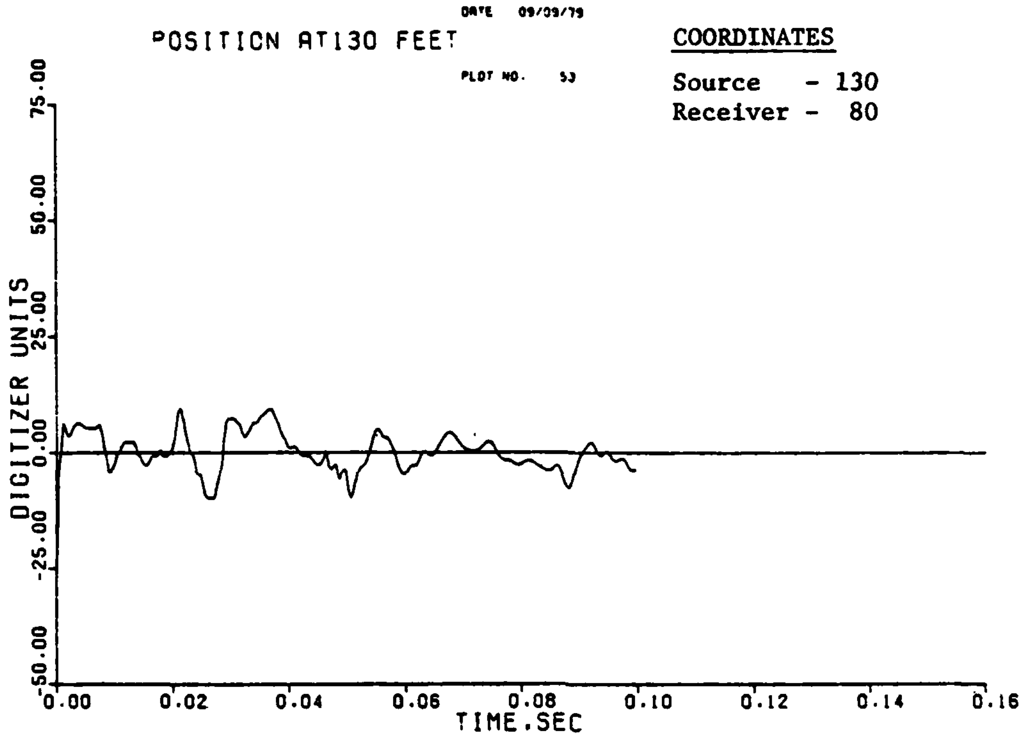


Figure 32. Digitized oscillograms for constant-spacing tests along 80W line, positions 120 and 125 ft



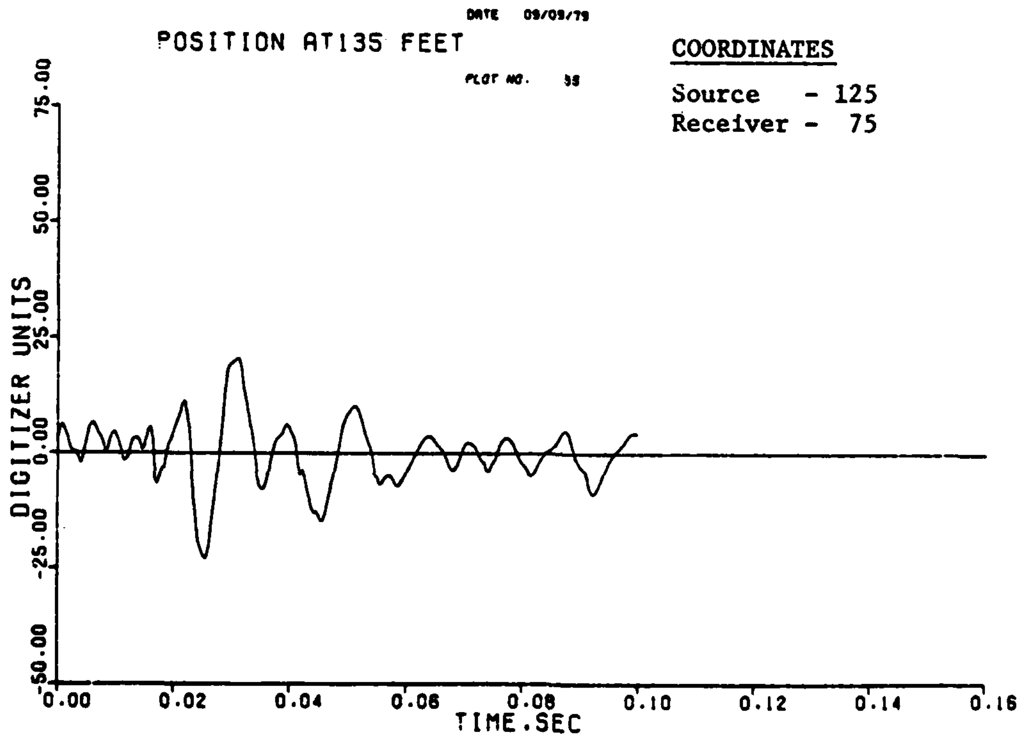
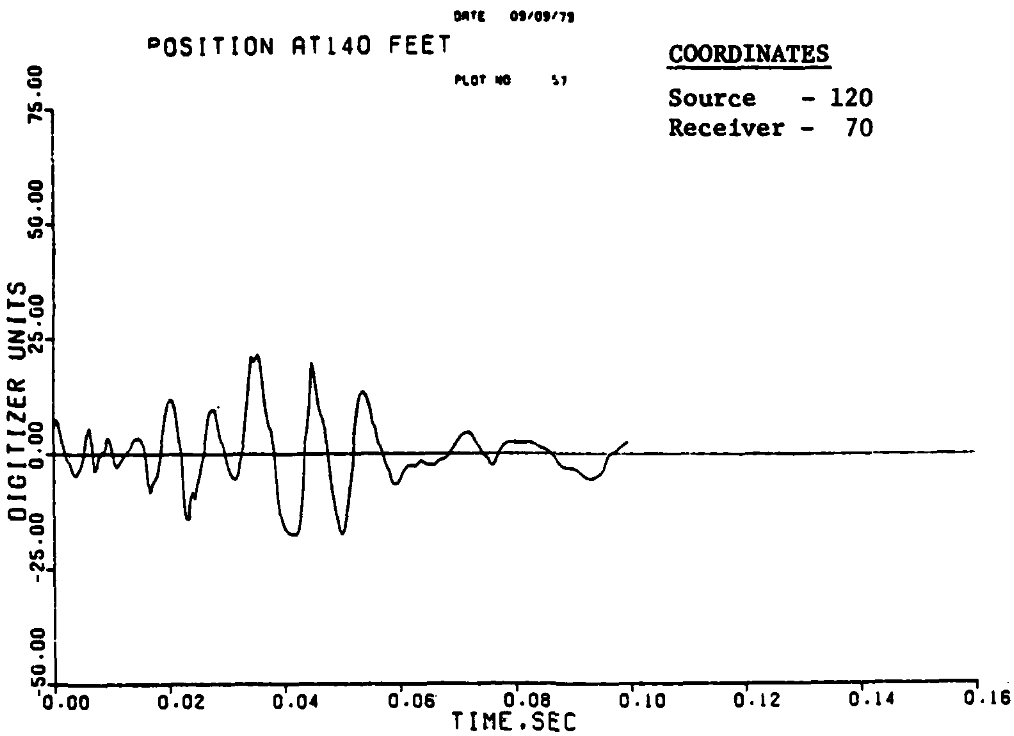


Figure 33. Digitized oscillograms for constant-spacing tests along 80W line, positions 130 and 135 ft



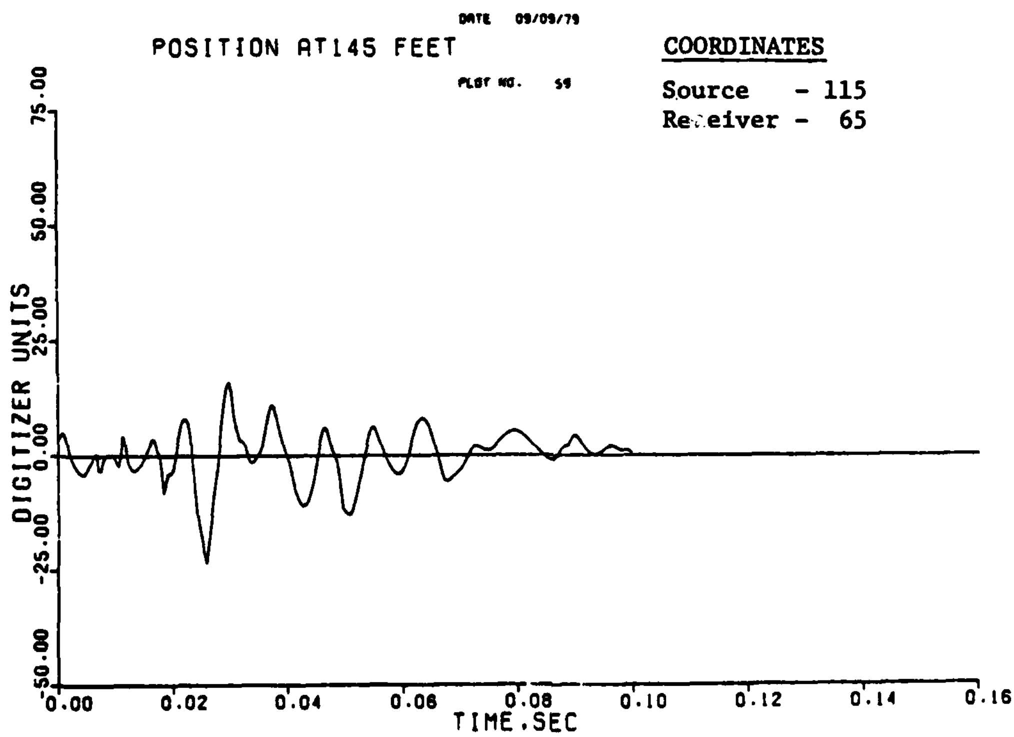
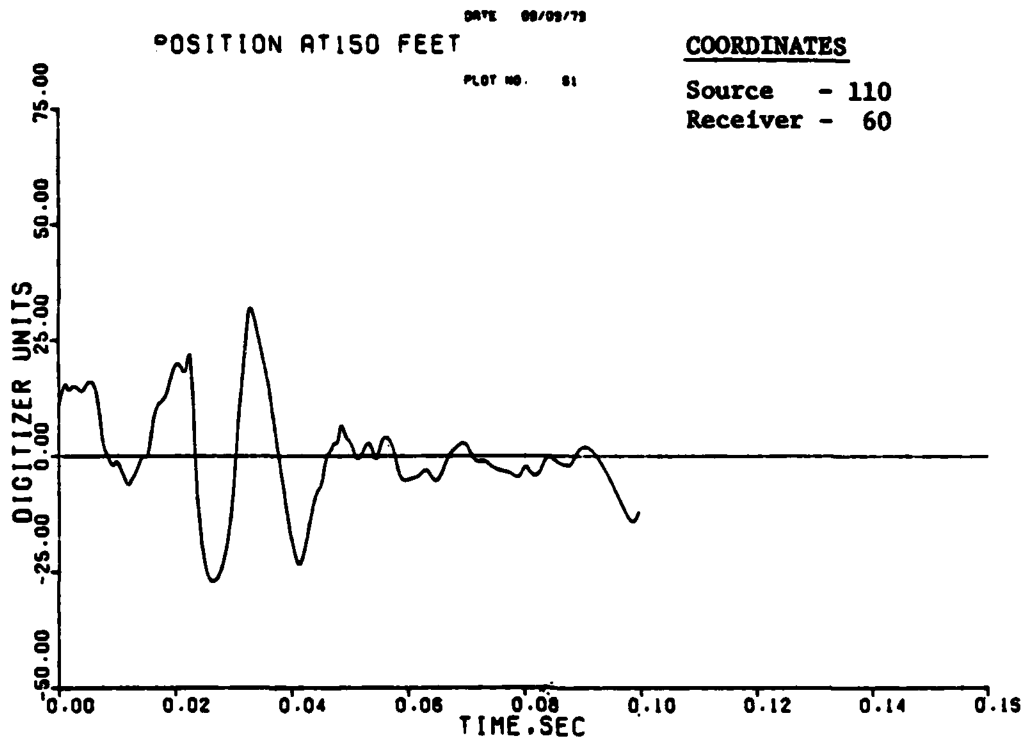


Figure 34. Digitized oscillograms for constant-spacing tests along 80W line, positions 140 and 145 ft



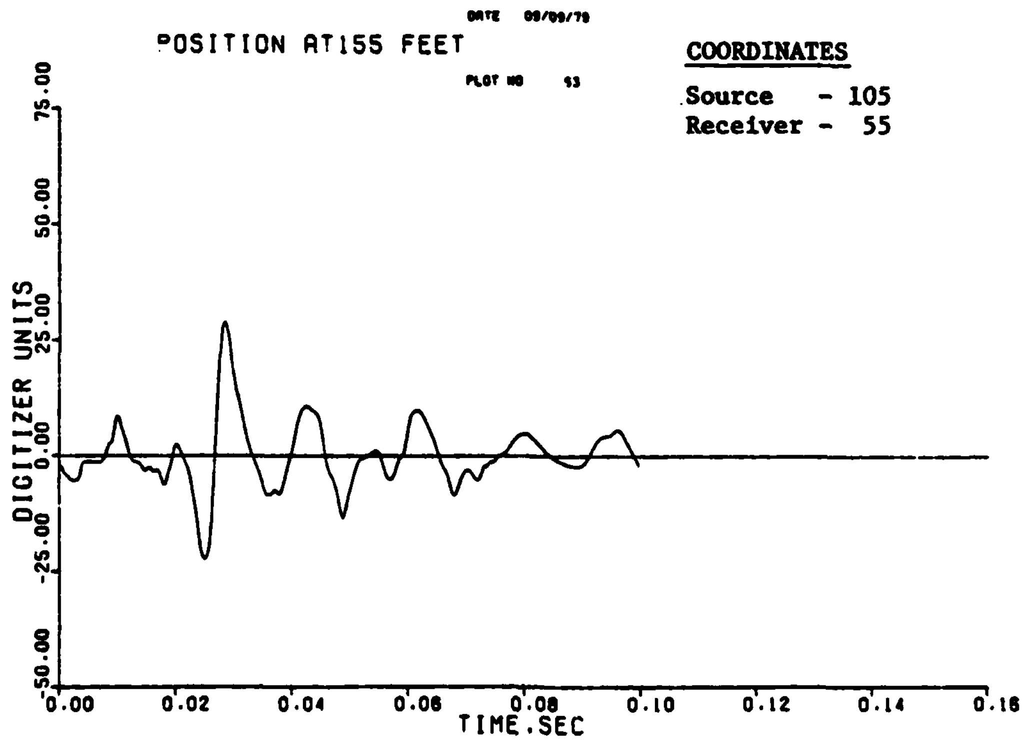
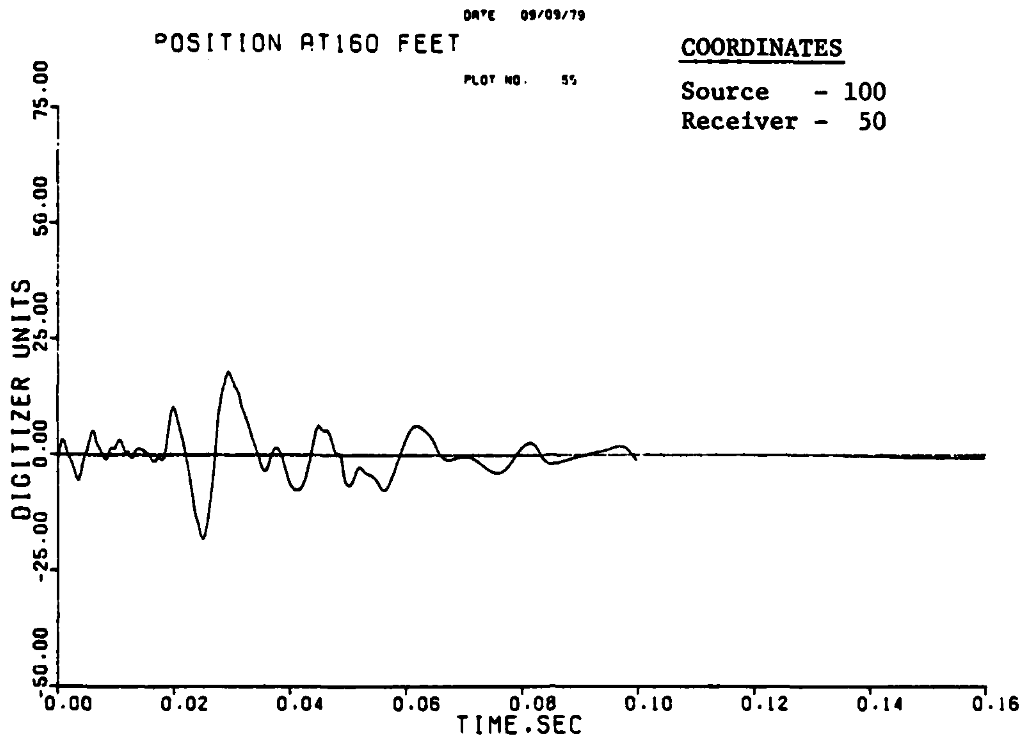


Figure 35. Digitized oscillograms for constant-spacing tests along 80W line, positions 150 and 155 ft



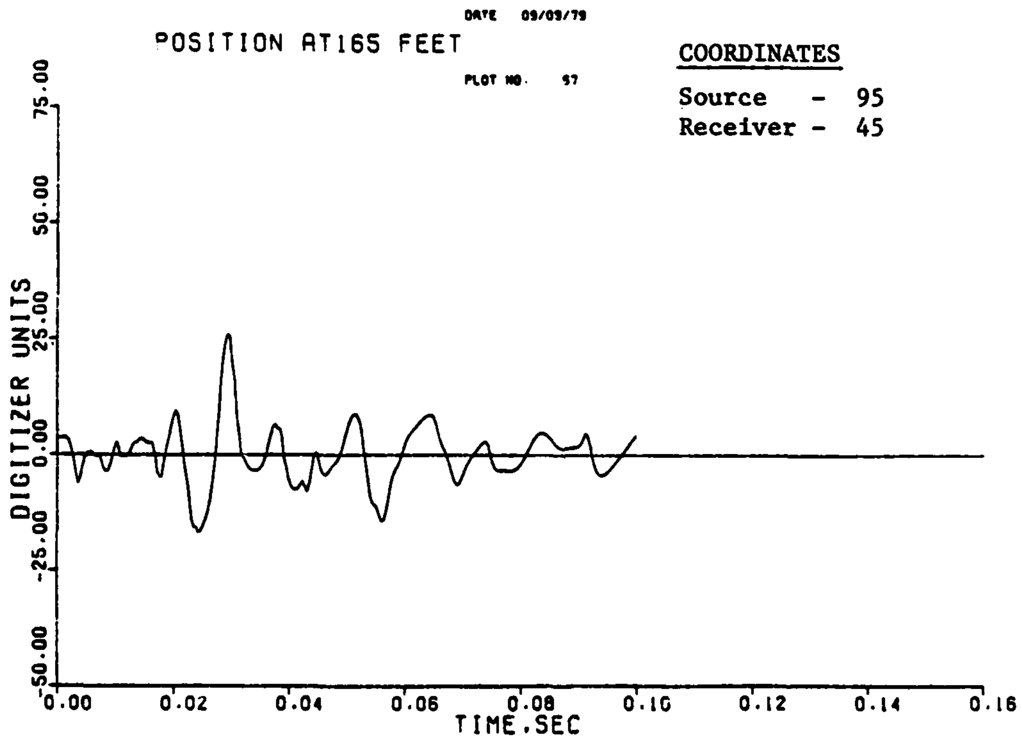


Figure 36. Digitized oscillograms for constant-spacing tests along 80W line, positions 160 and 165 ft

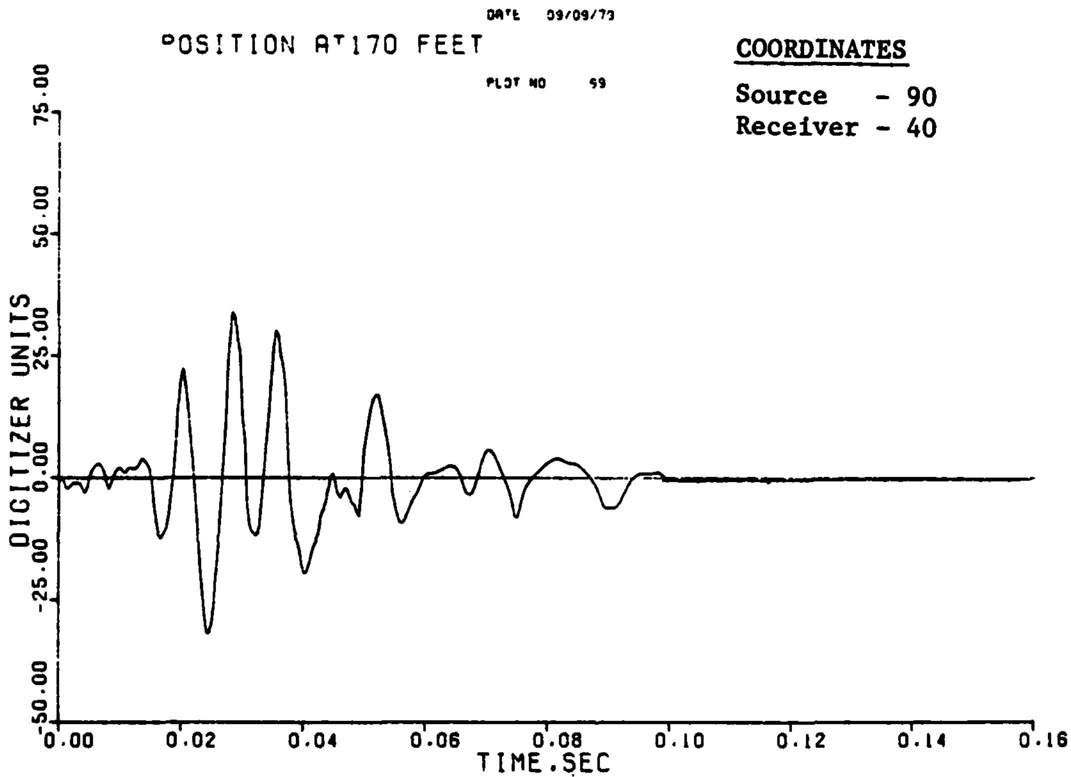


Figure 37. Digitized oscillogram for constant-spacing tests along 80W line, position 170 ft

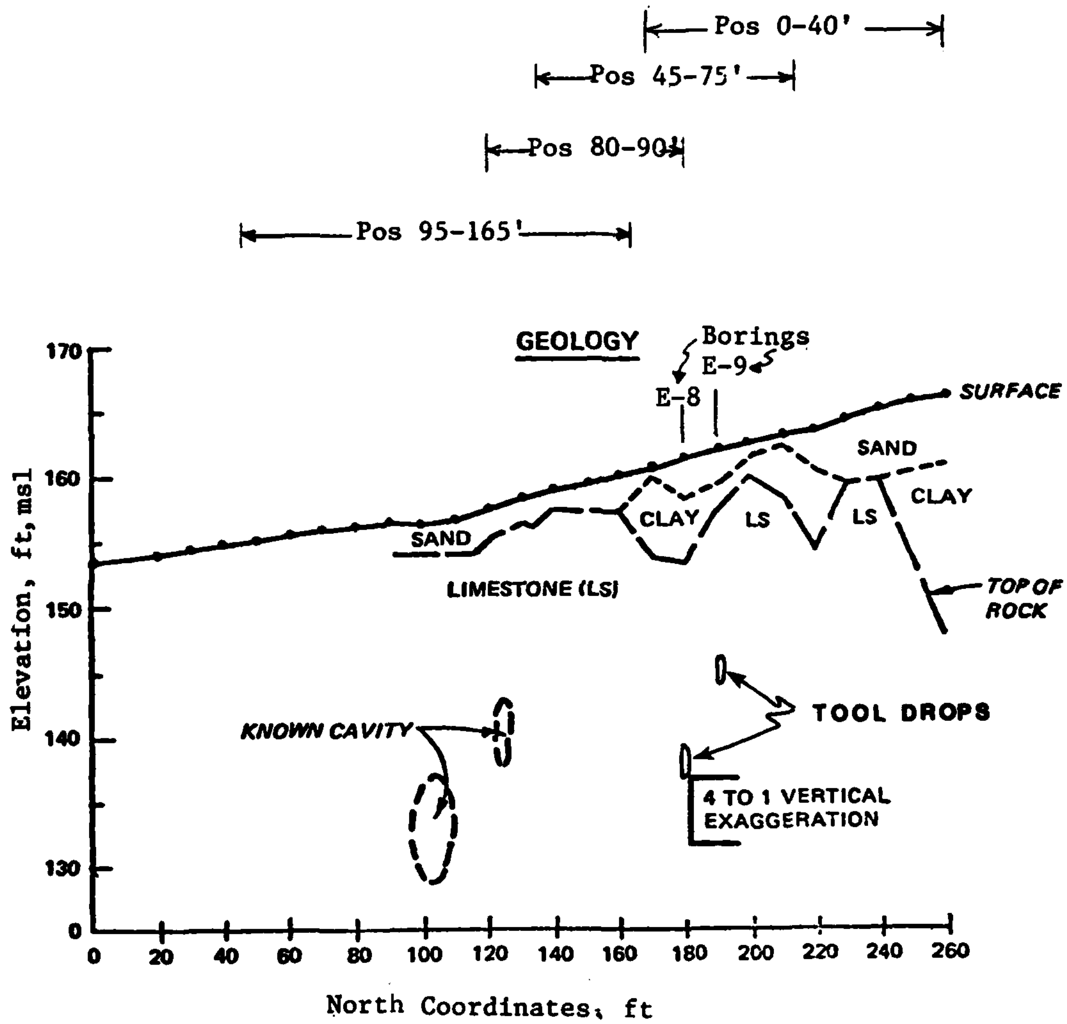


Figure 38. Geologic profile along 80W line showing constant-spacing positions

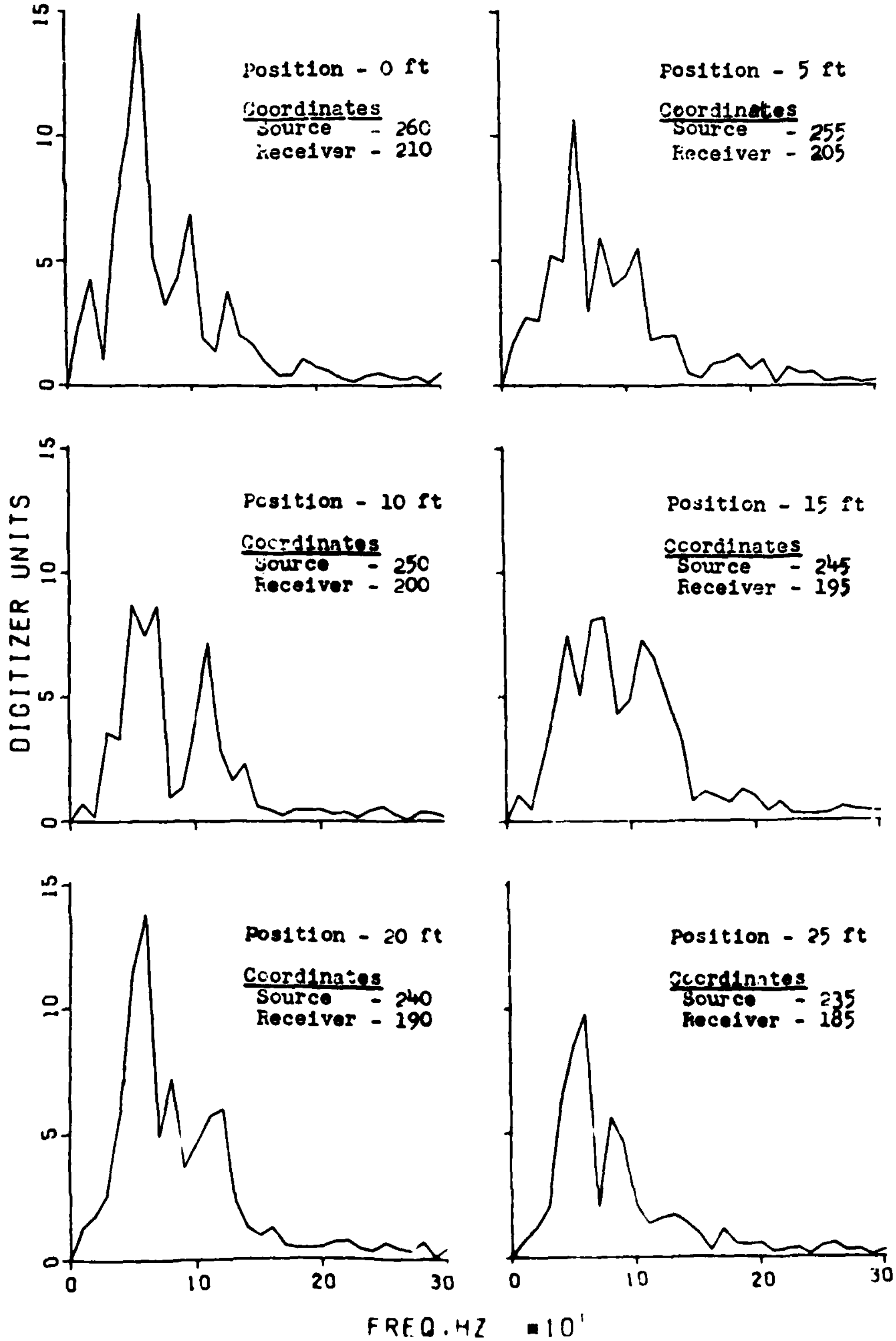


Figure 39. Relative spectral constant for constant-spacing tests along 80W line, positions 0 through 25 ft

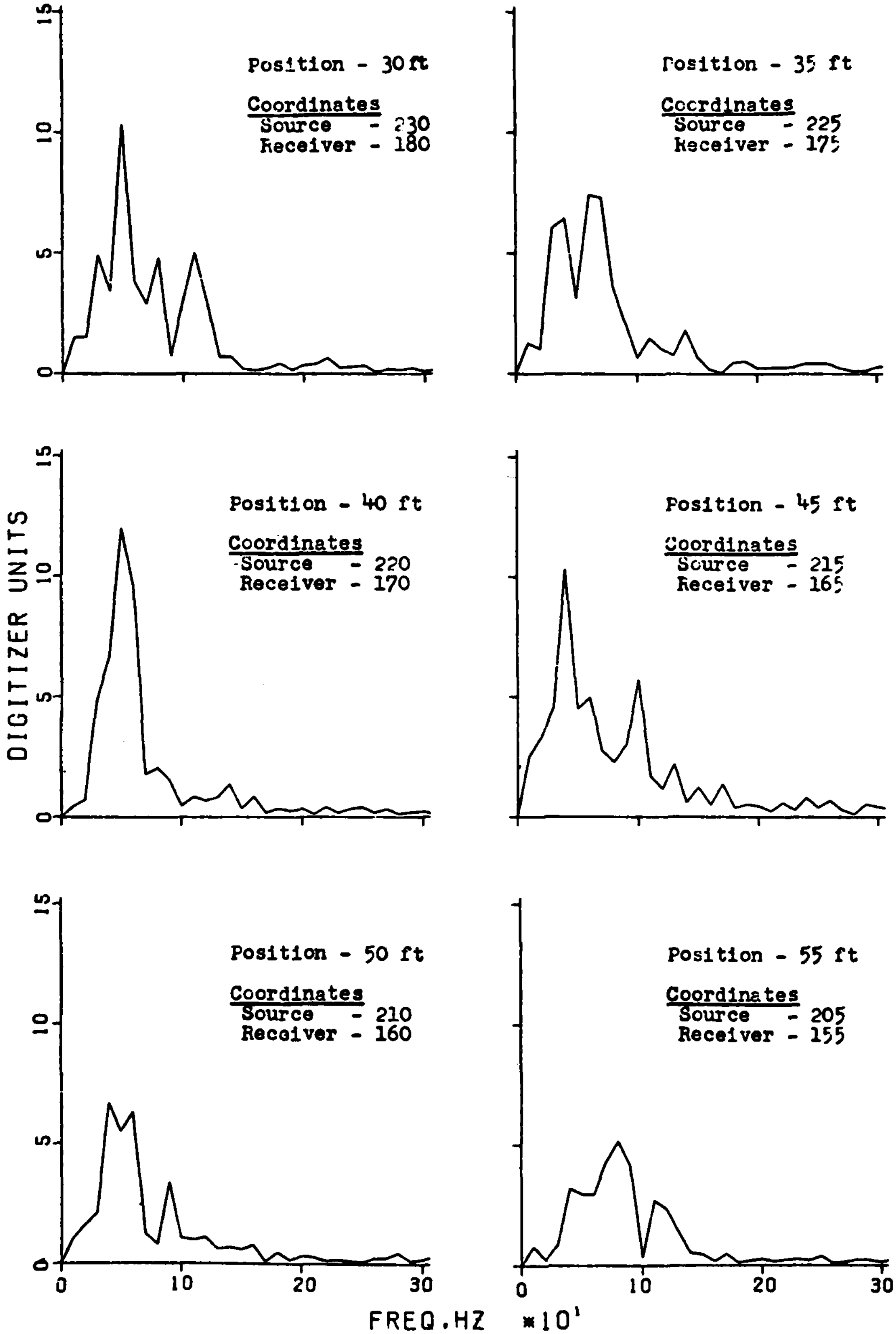


Figure 40. Relative spectral constant for constant-spacing tests along 80W line, positions 30 through 55 ft

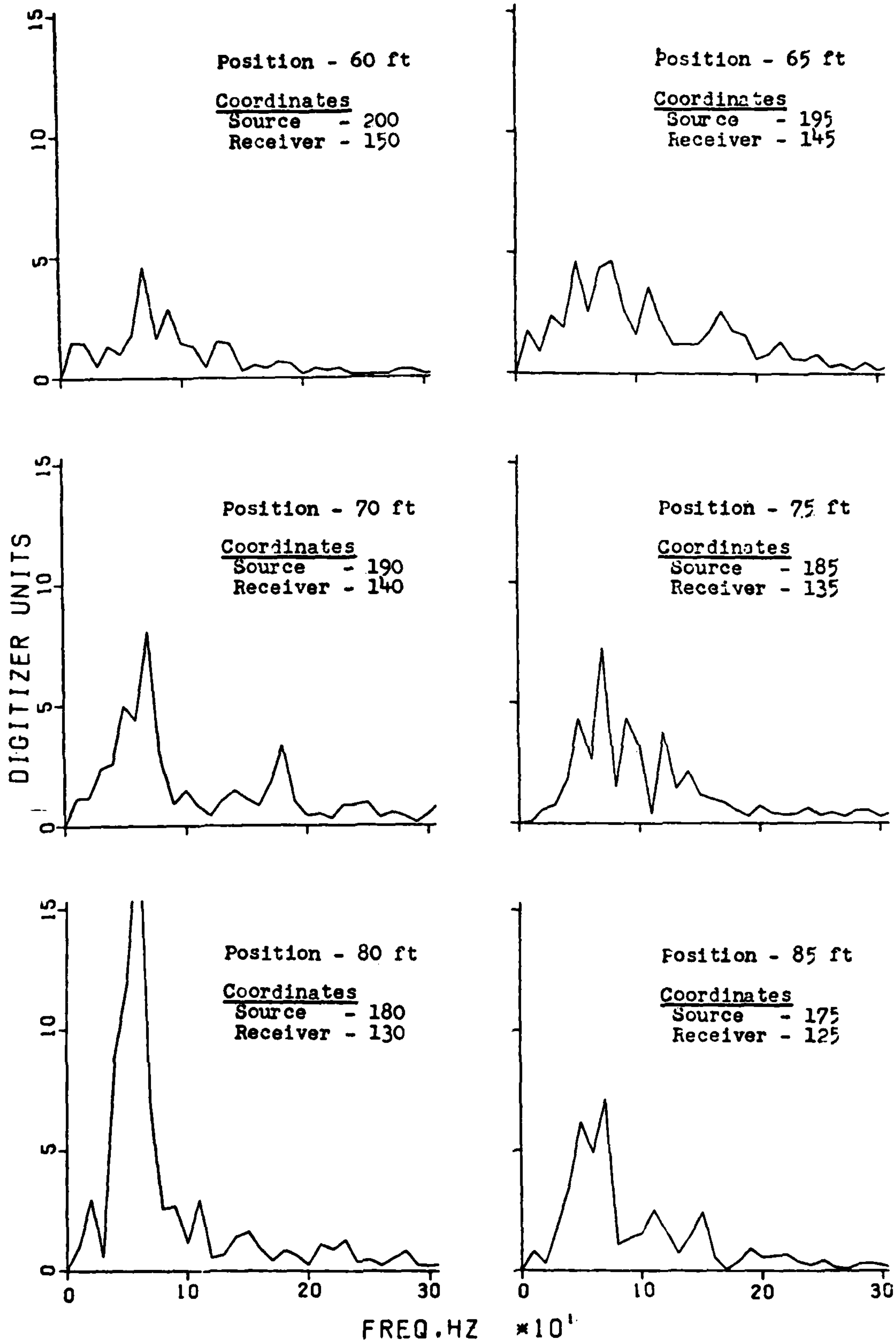


Figure 41. Relative spectral constant for constant-spacing tests along 80W line, positions 60 through 85 ft

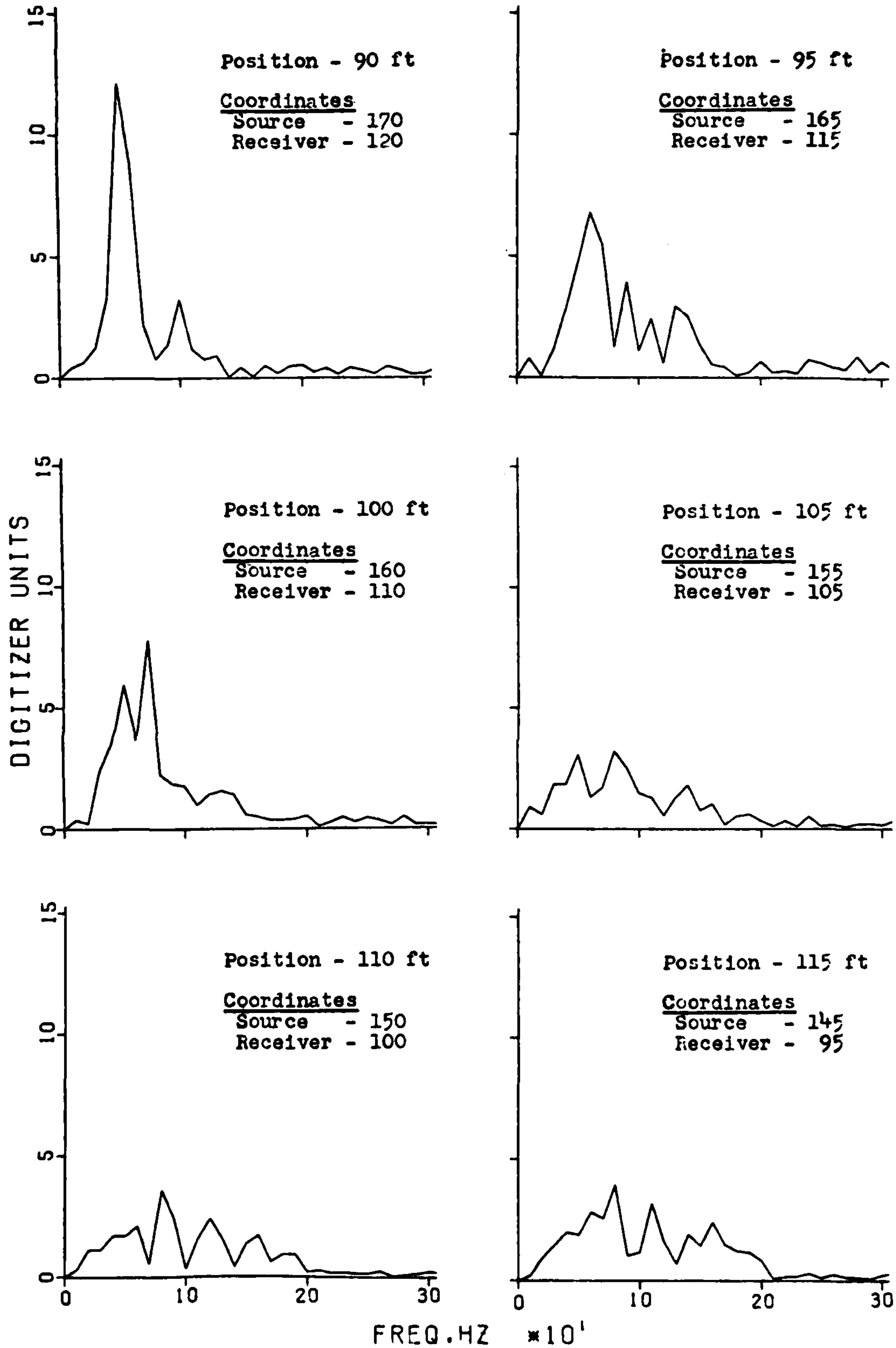


Figure 42. Relative spectral constant for constant-spacing tests along 80W line, positions 90 through 115 ft

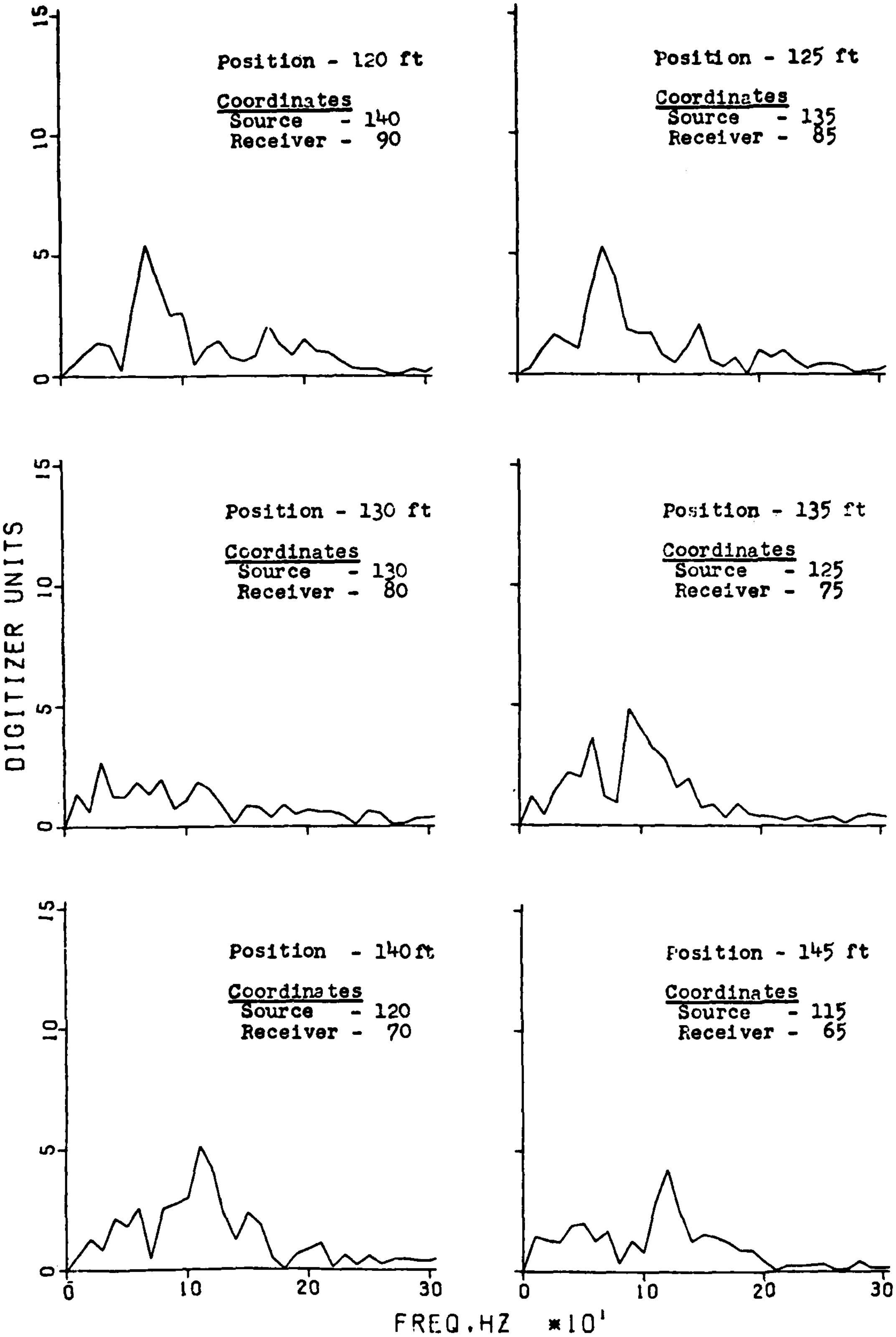


Figure 43. Relative spectral constant for constant-spacing tests along 80W line, positions 120 through 145 ft

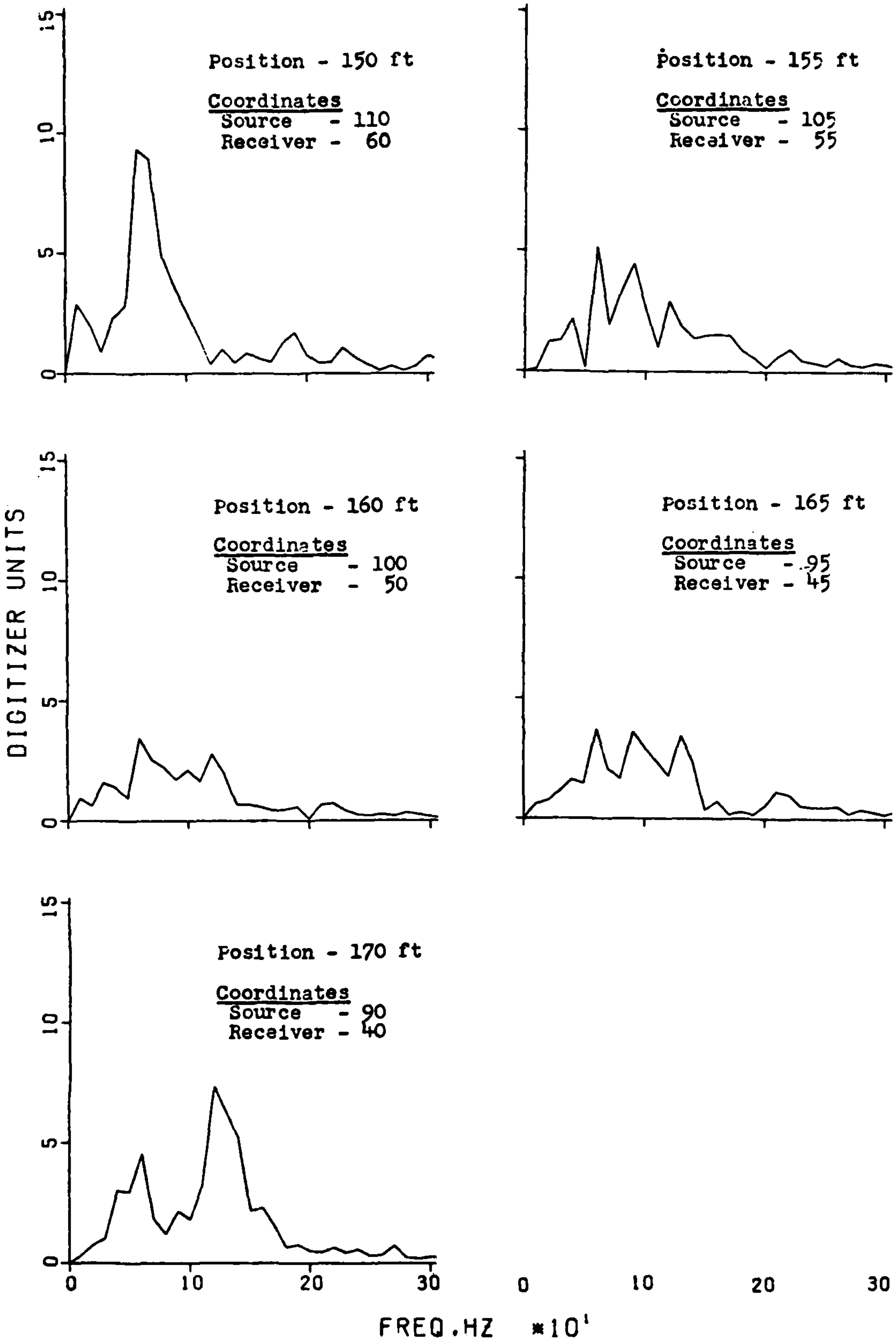


Figure 44. Relative spectral constant for constant-spacing tests along 80W line, positions 150 through 170 ft

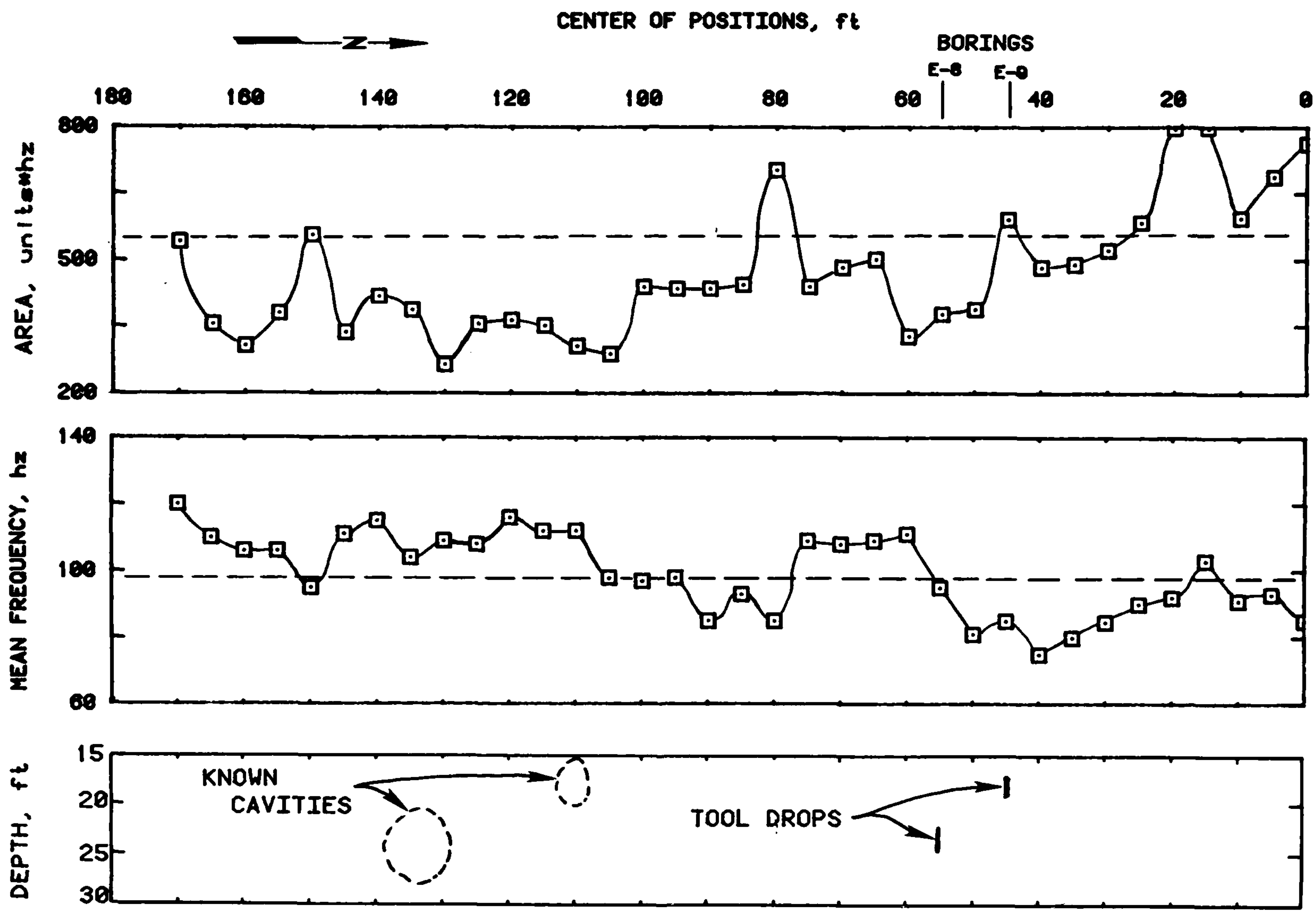


Figure 45. Area and mean frequency versus center of positions plots for constant-spacing test 1 along 80W line

Position 0 ft	Source - 0 ft	Receiver - -25 ft
Position 5 ft	Source - 5 ft	Receiver - -20 ft
Position 10 ft	Source - 10 ft	Receiver - -15 ft
Position 15 ft	Source - 15 ft	Receiver - -10 ft
Position 20 ft	Source - 20 ft	Receiver - -5 ft
Position 25 ft	Source - 25 ft	Receiver - 0 ft
Position 30 ft	Source - 30 ft	Receiver - 5 ft
Position 35 ft	Source - 35 ft	Receiver - 10 ft
Position 40 ft	Source - 40 ft	Receiver - 15 ft
Position 45 ft	Source - 45 ft	Receiver - 20 ft
Position 50 ft	Source - 50 ft	Receiver - 25 ft
Position 55 ft	Source - 55 ft	Receiver - 30 ft
Position 60 ft	Source - 60 ft	Receiver - 35 ft

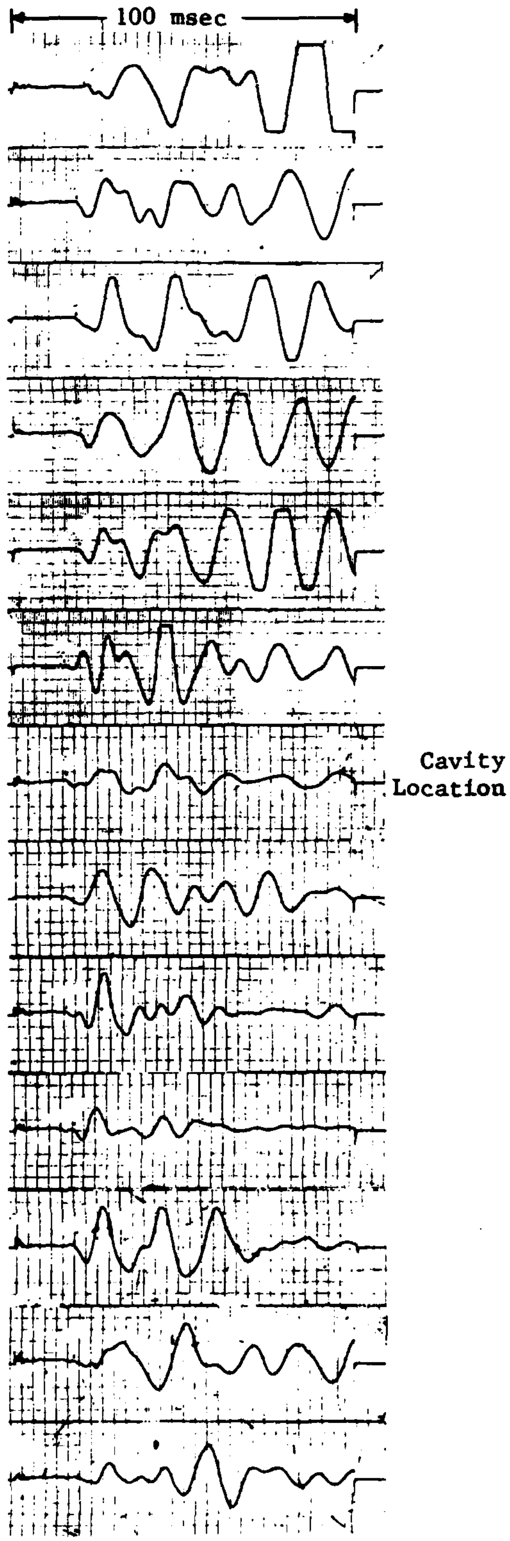


Figure 46. Oscillograms obtained from constant-spacing test 2

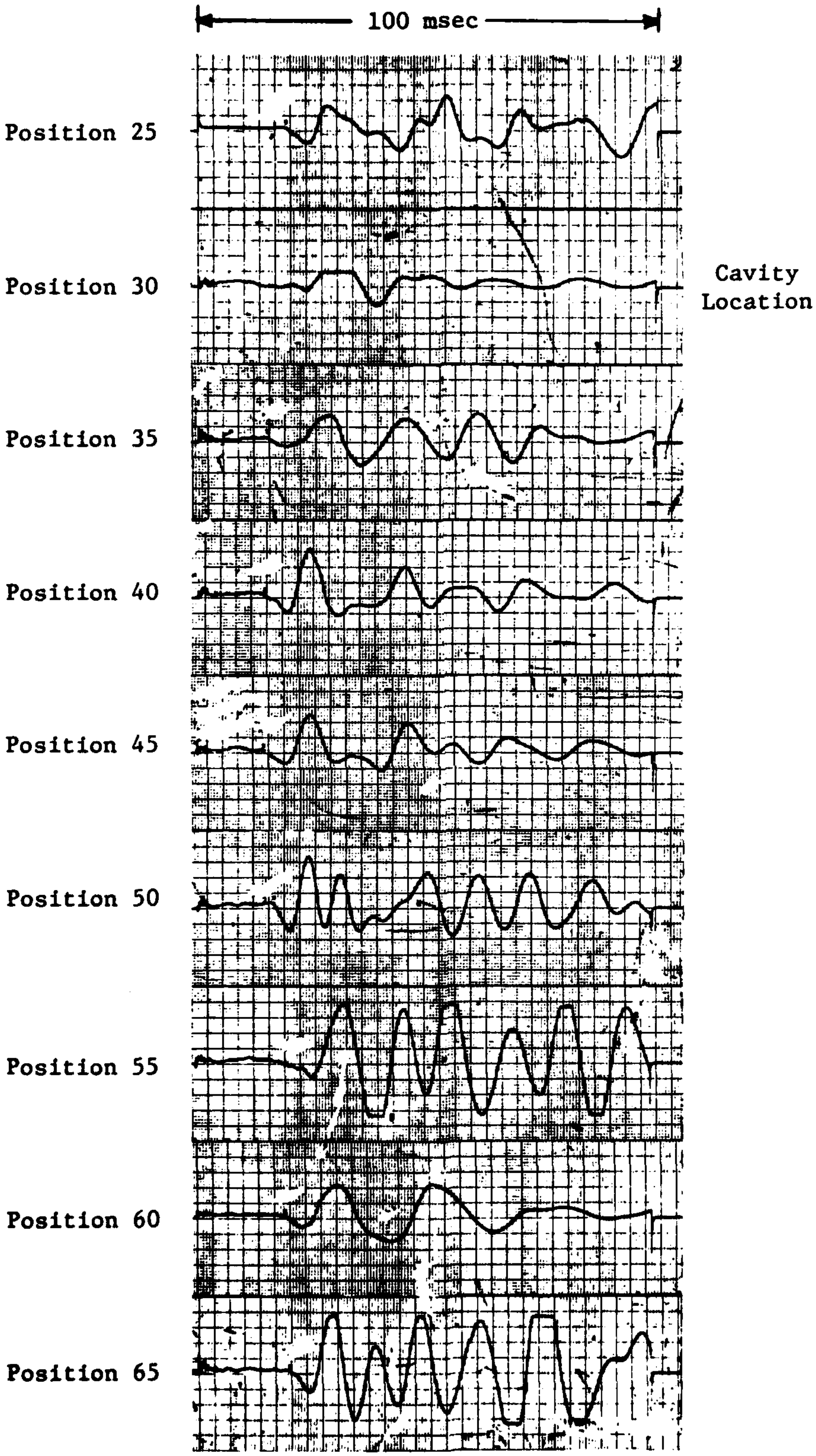


Figure 47. Oscillograms obtained from constant-spacing test 3

Hole No. 68, 245

DRILLING LOG	DIVISION: Geotechnical Lab	INSTALLATION: WES	SHEET 1 OF 1 SHEETS
1. PROJECT: Medford Cave Site		10. SIZE AND TYPE OF BIT: 3" core	
2. LOCATION (Coordinates or Station)		11. DATUM FOR ELEVATION SHOWN (TBM or MSL)	
3. DRILLING AGENCY: Mobile District Corps of Engineers		12. MANUFACTURER'S DESIGNATION OF DRILL: Failing 1500	
4. HOLE NO. (As shown on drawing title and file number): 68, 245		13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN	DISTURBED: -- / UNDISTURBED: --
5. NAME OF DRILLER: Herbert Owens		14. TOTAL NUMBER CORE BOXES: 1	
6. DIRECTION OF HOLE: [X] VERTICAL [ ] INCLINED ____ DEG. FROM VERT.		15. ELEVATION GROUND WATER: none	
		16. DATE HOLE	STARTED: 11 June 80 / COMPLETED: 11 June 80
7. THICKNESS OF OVERBURDEN: 3.5 ft		17. ELEVATION TOP OF HOLE: --	
8. DEPTH DRILLED INTO ROCK: 22.5 ft		18. TOTAL CORE RECOVERY FOR BORING: 5 %	
9. TOTAL DEPTH OF HOLE: 26.0 ft		19. SIGNATURE OF INSPECTOR: Charles W. Miller	

ELEVATION a	DEPTH ft b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		sand, black grading into black clay with ls nodules	no sample		flight auger to 3.5 ft
			Ls, white, soft, fossiliferous; most of core sample was hard fossil casts and molds; soft is washed away	Run 1 21%	Box 1	lost water return at 6 ft, no cavities
	10			Run 2 5%		RQD = 0
	20			Run 3 4%		
	30					jammed core barrel into soft ls the last 0.2 ft; ls was very soft and granular

ENG FORM 1836 MAR 71 PREVIOUS EDITIONS ARE OBSOLETE (TRANSLUCENT) | PROJECT: Medford Cave Site | HOLE NO. 68, 245

Figure 48. Drilling log for boring E-24

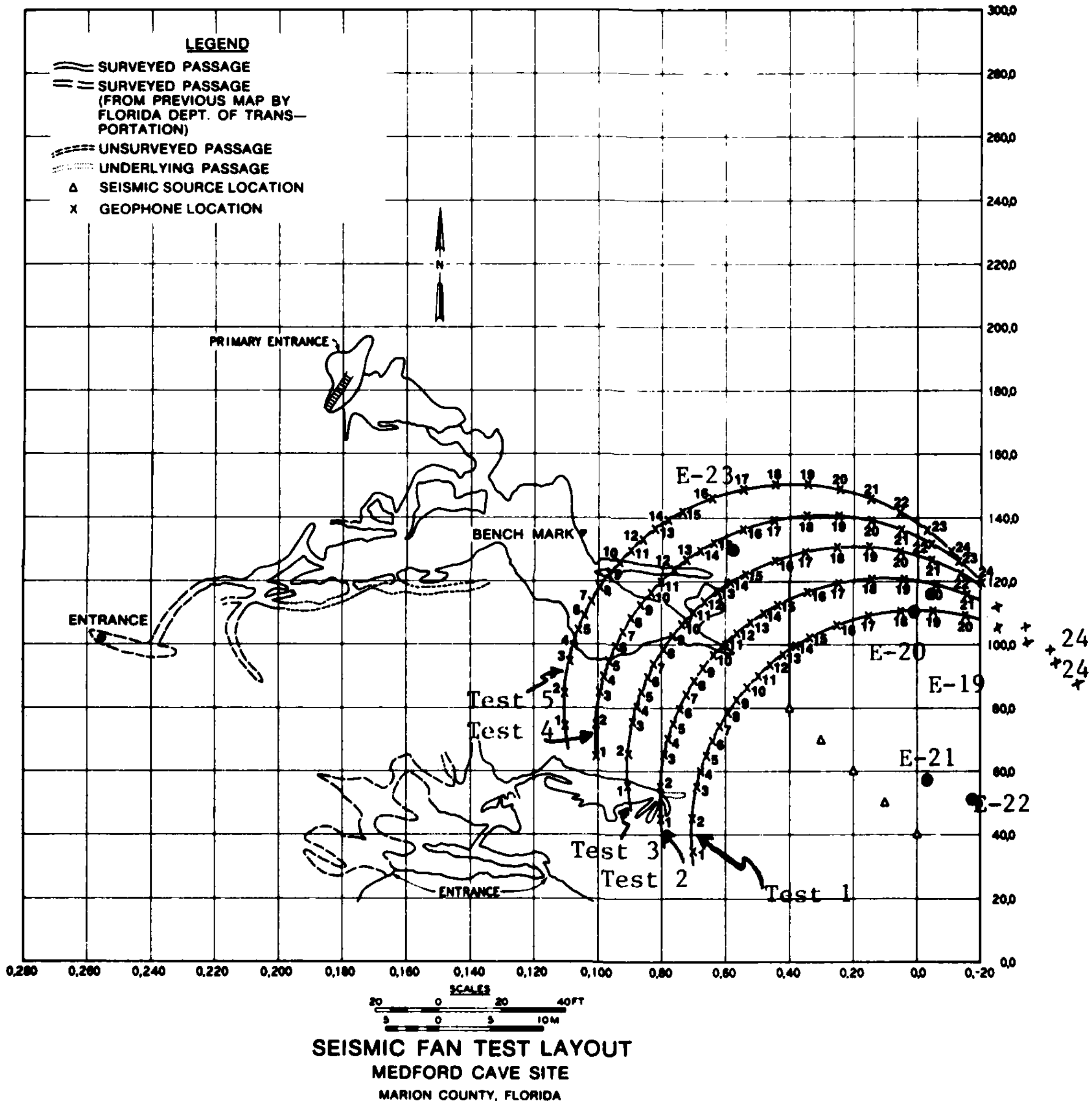


Figure 49. Seismic fan test layout

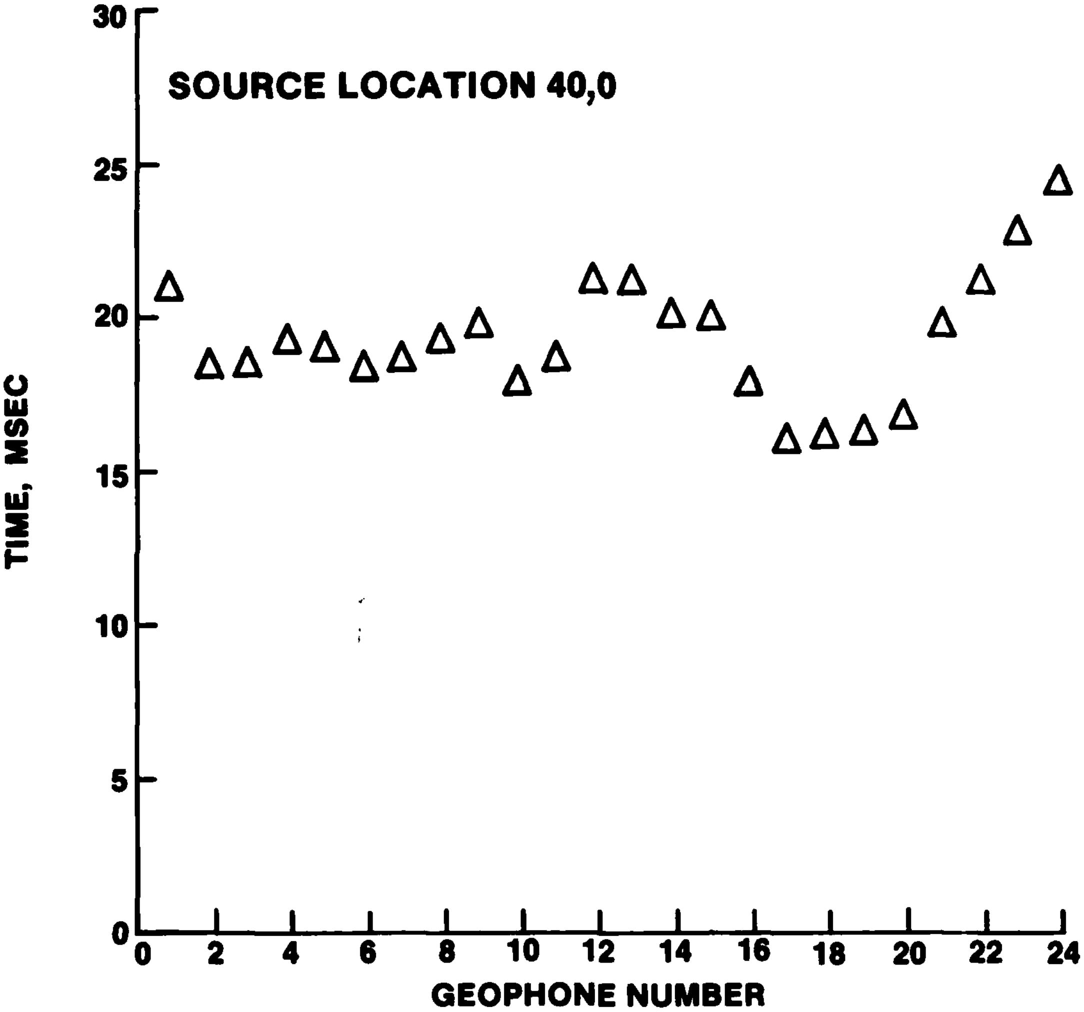


Figure 50. P-wave arrival time versus distance for fan test 1

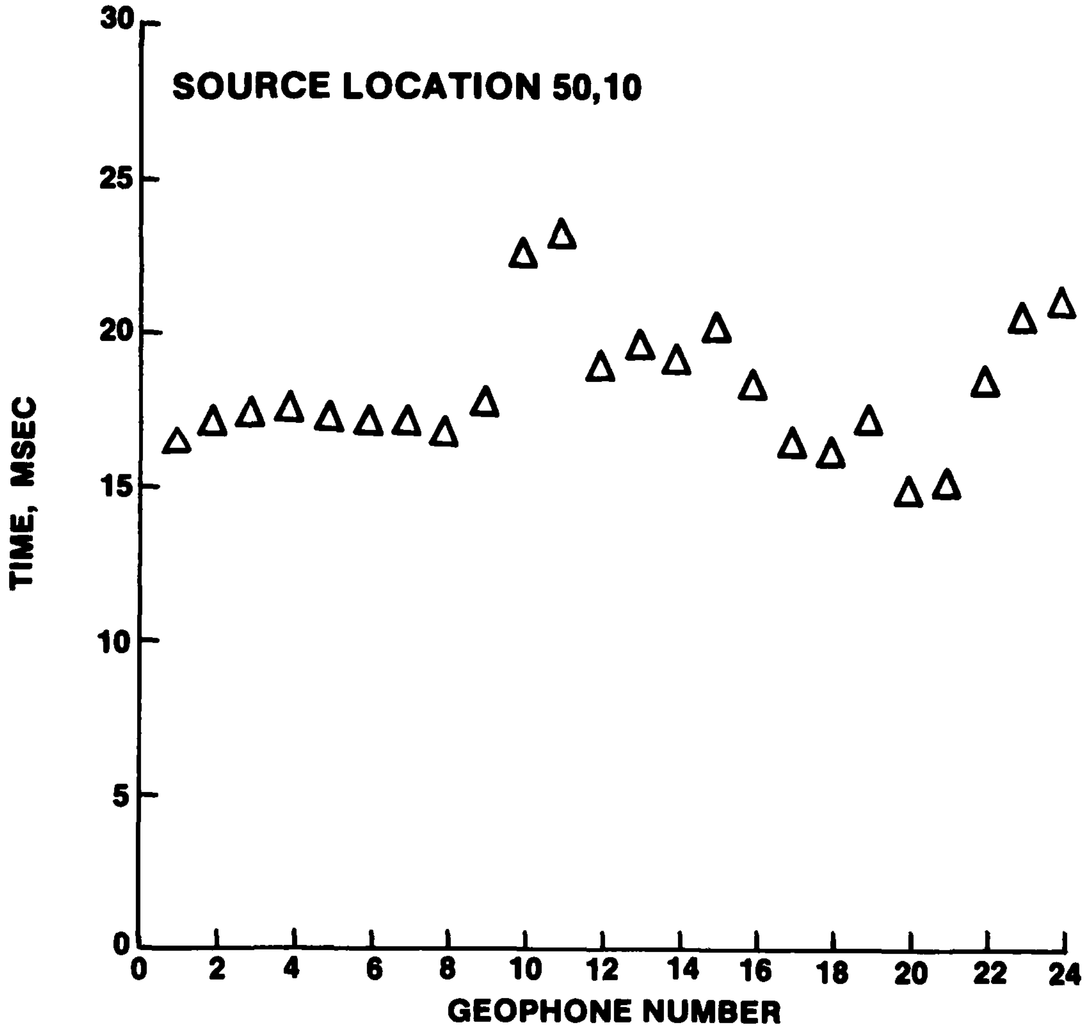


Figure 51. P-wave arrival time versus distance for fan test 2

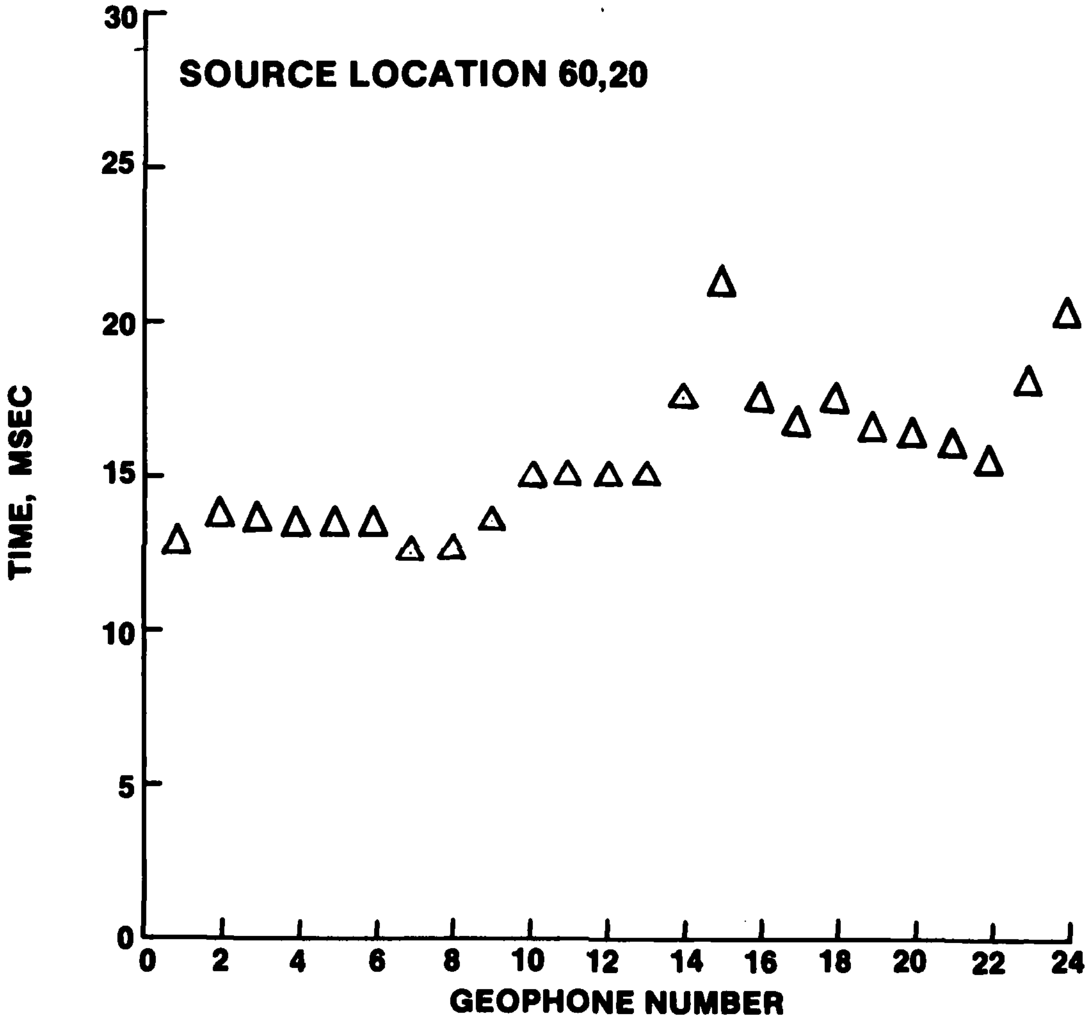


Figure 52. P-wave arrival time versus distance for fan test 3

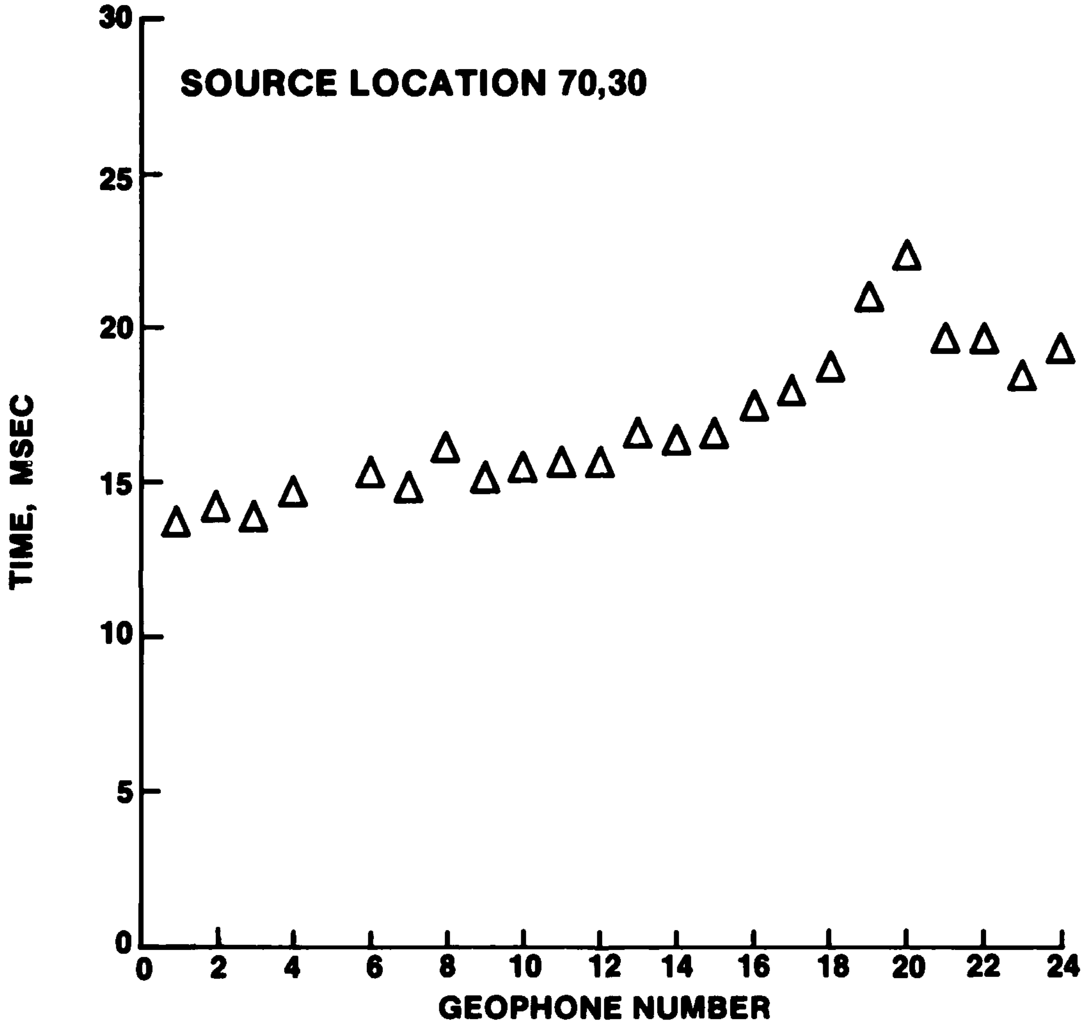


Figure 53. P-wave arrival time versus distance for fan test 4

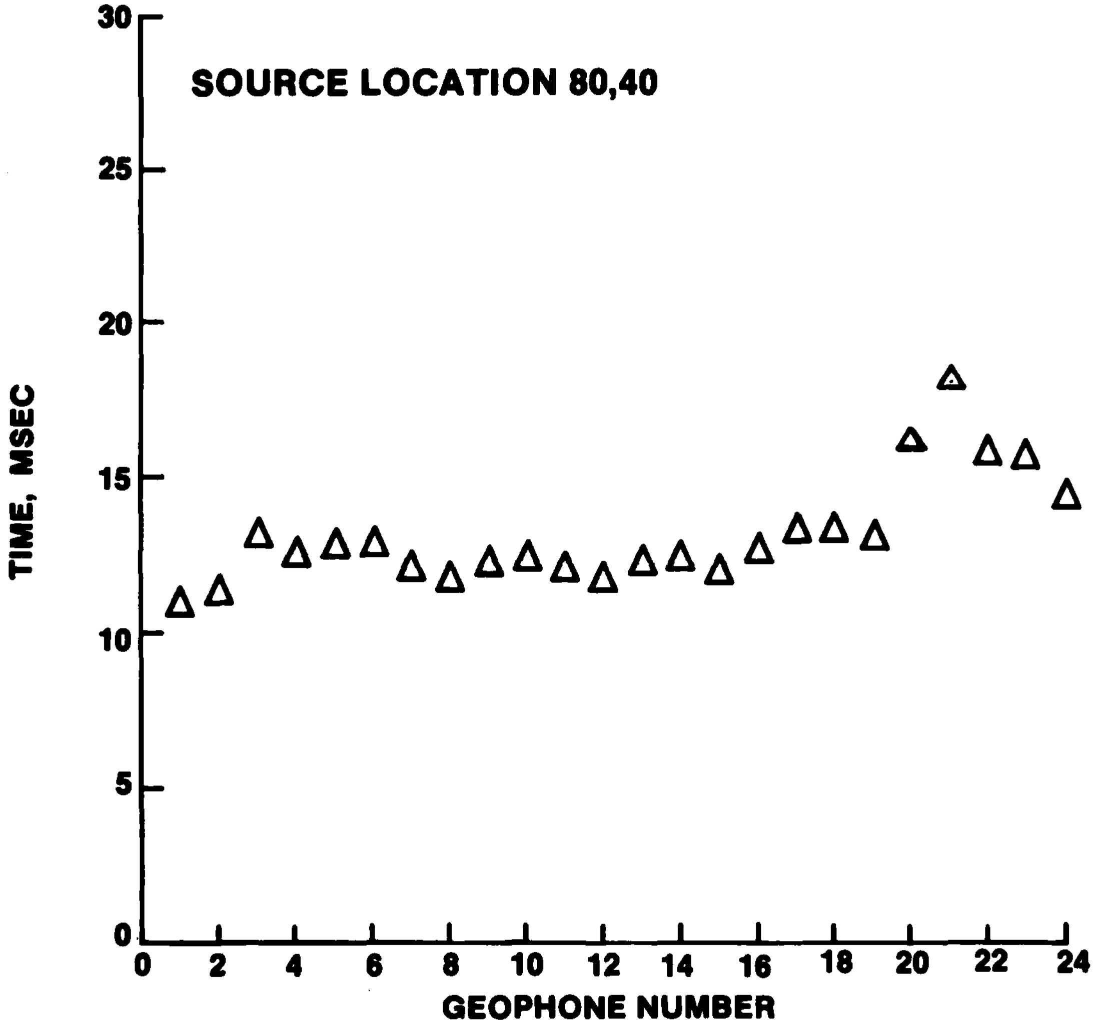


Figure 54. P-wave arrival time versus distance for fan test 5

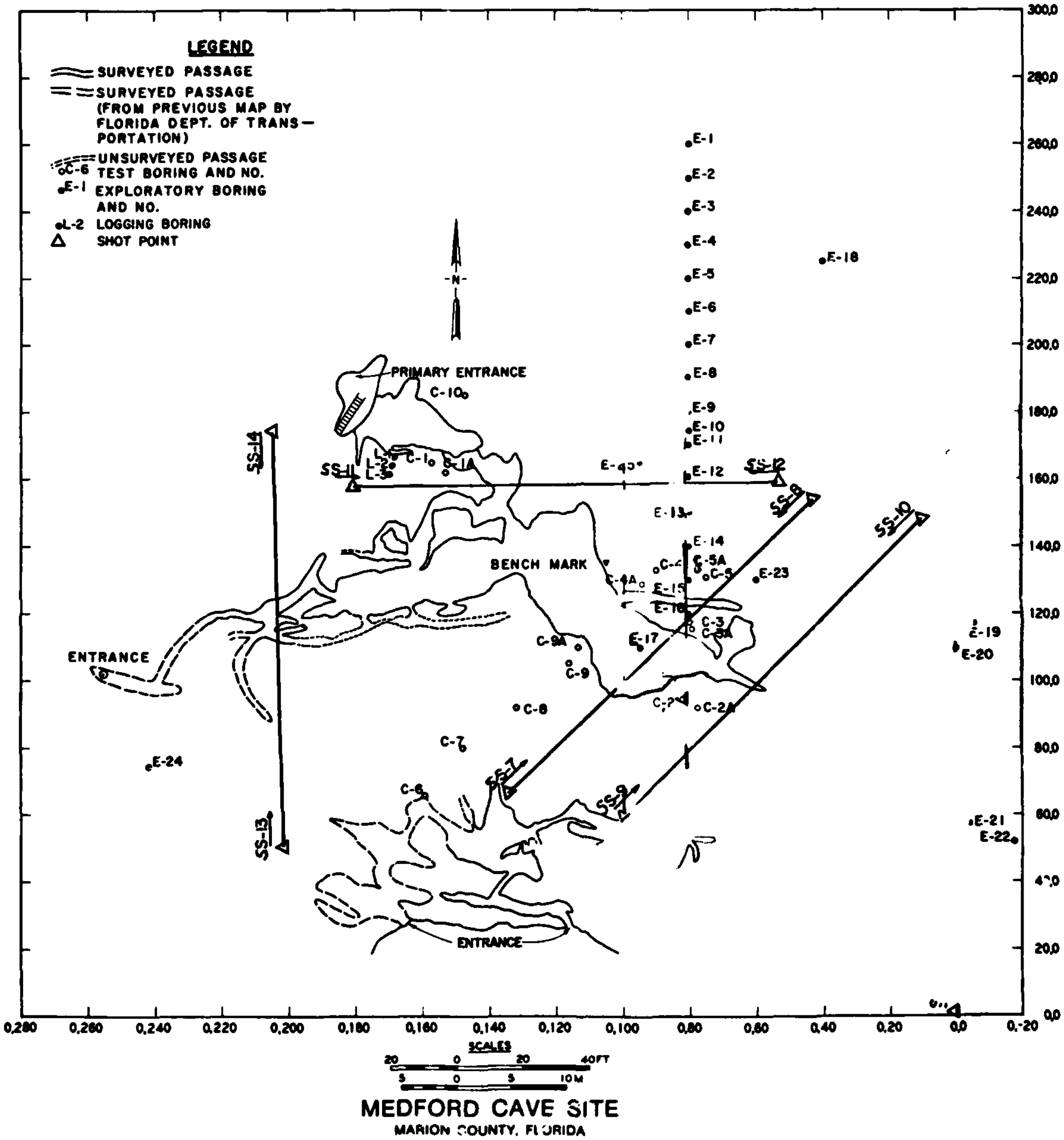


Figure 55. Surface shear wave test layout

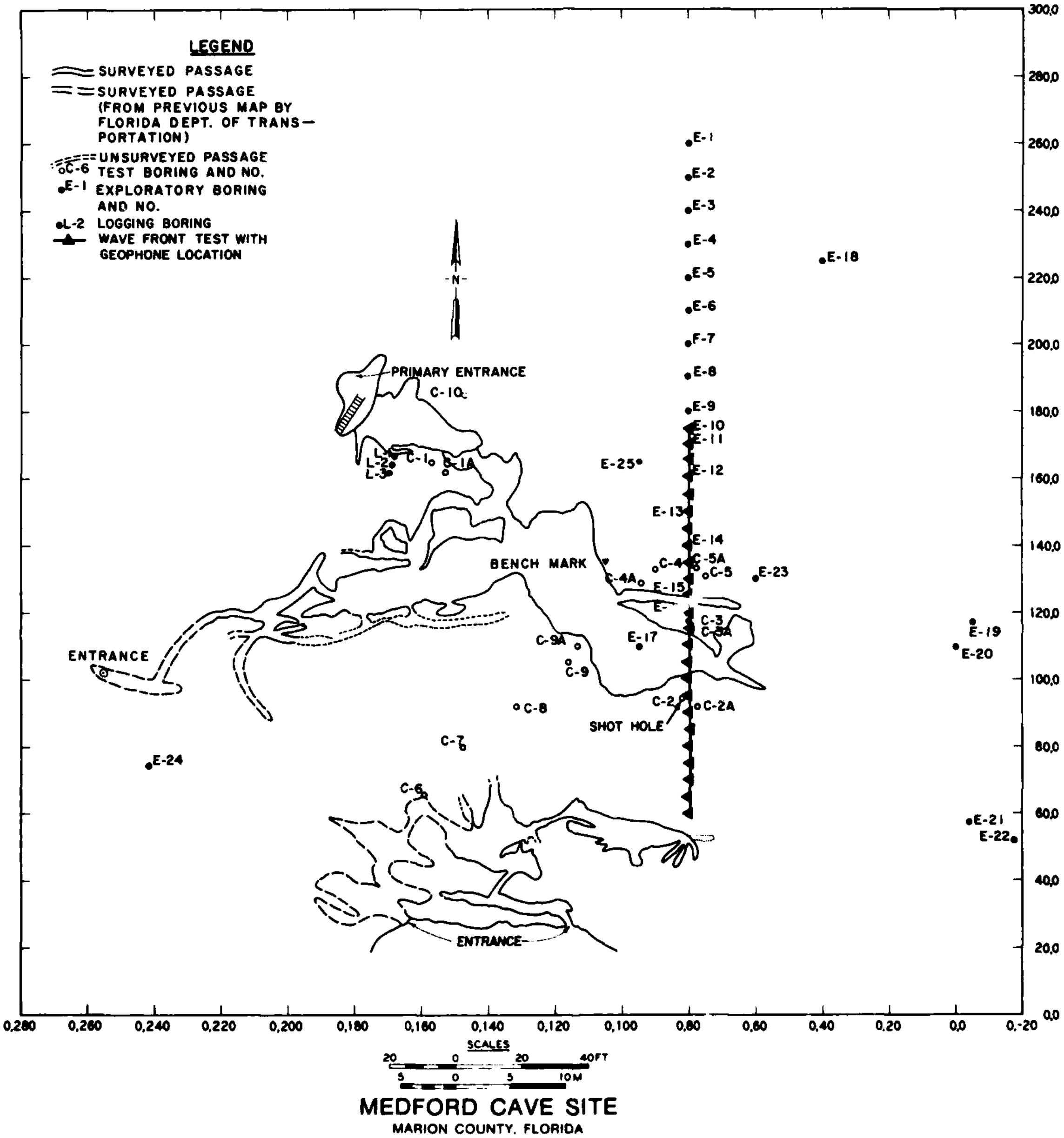


Figure 56. Uphole refraction test layout